

Direct Detection of the Dark Mediated DM

Yuhsin Tsai

UC Davis

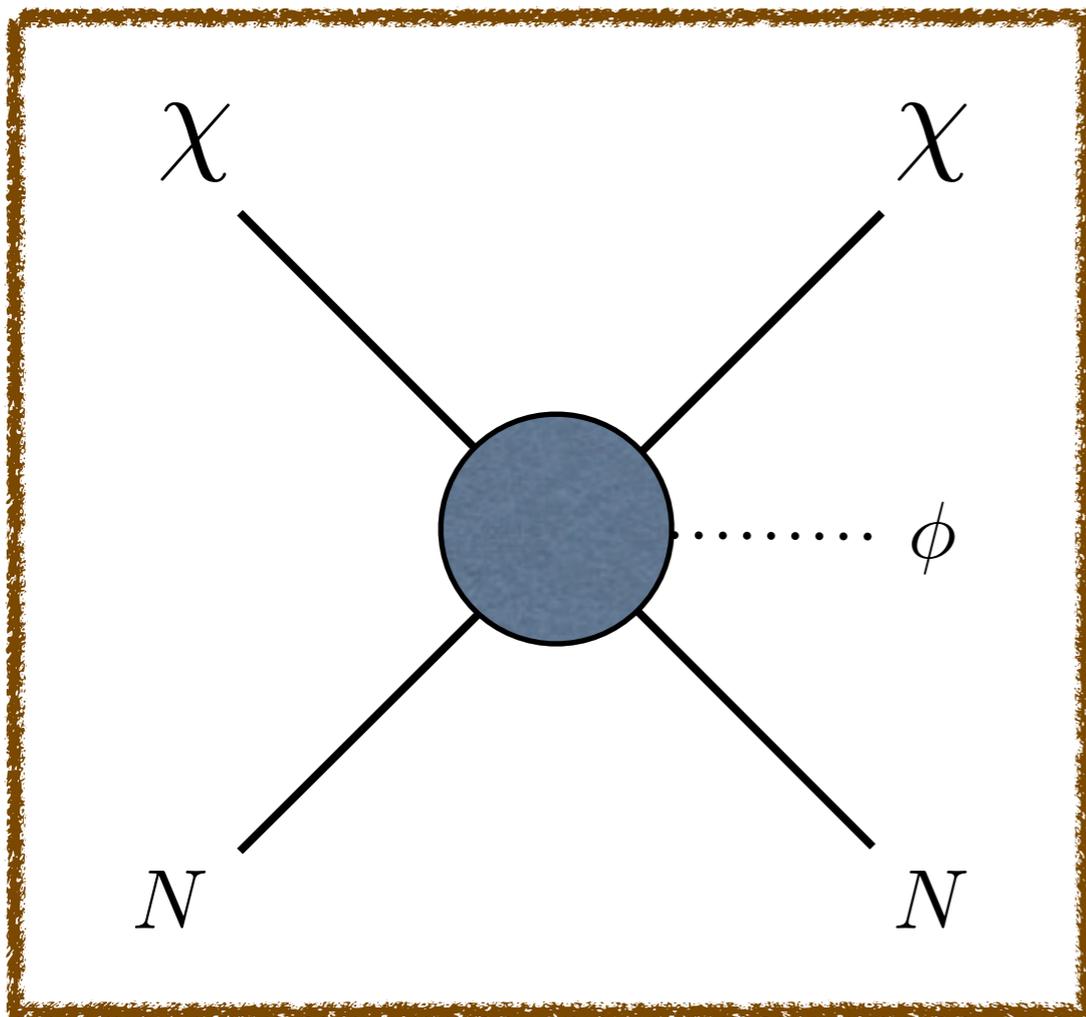
In collaboration with [David Curtin](#) and [Ze'ev Surujon](#)

[1312.2618](#) and [1405.1034](#)

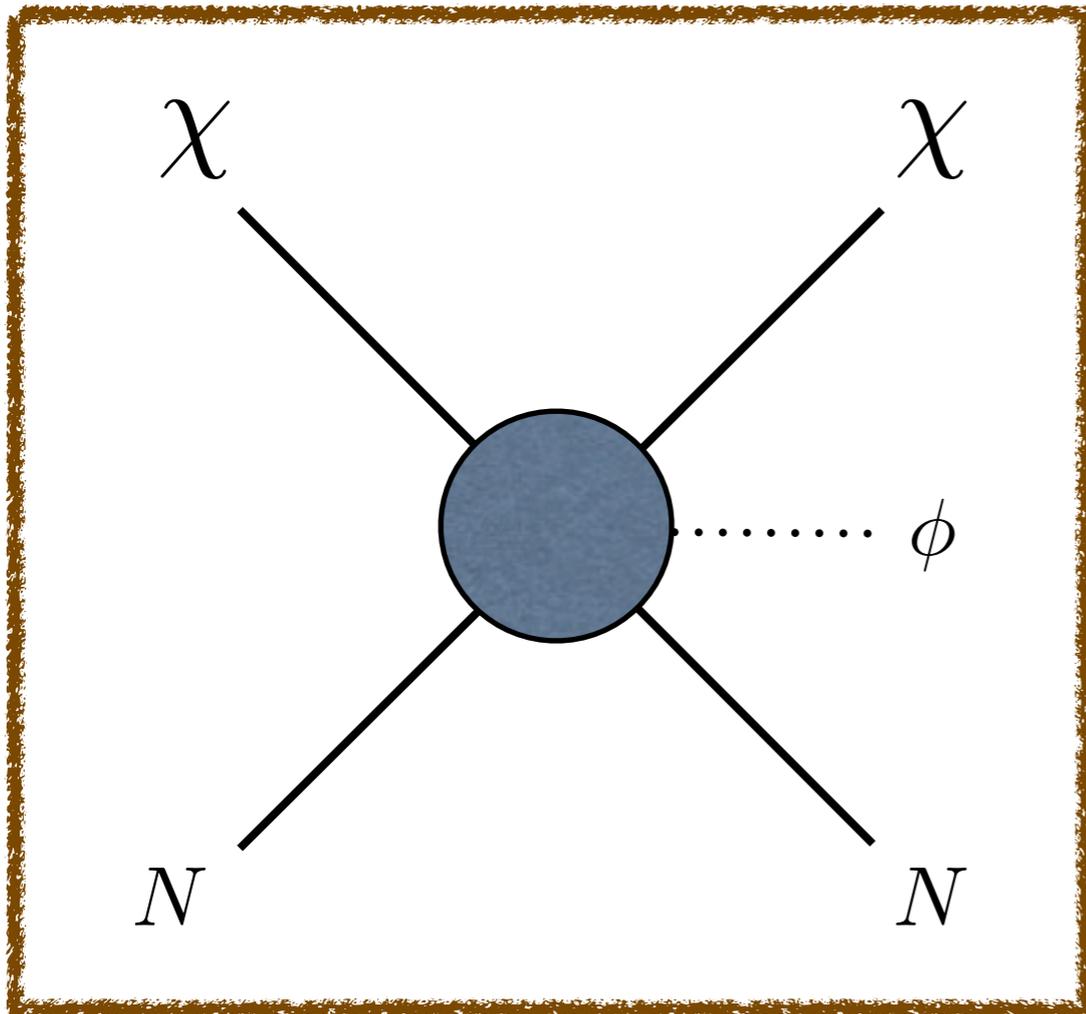
New Perspectives, Fermilab, April 29 2014

Three questions

How does the direct detection look like?



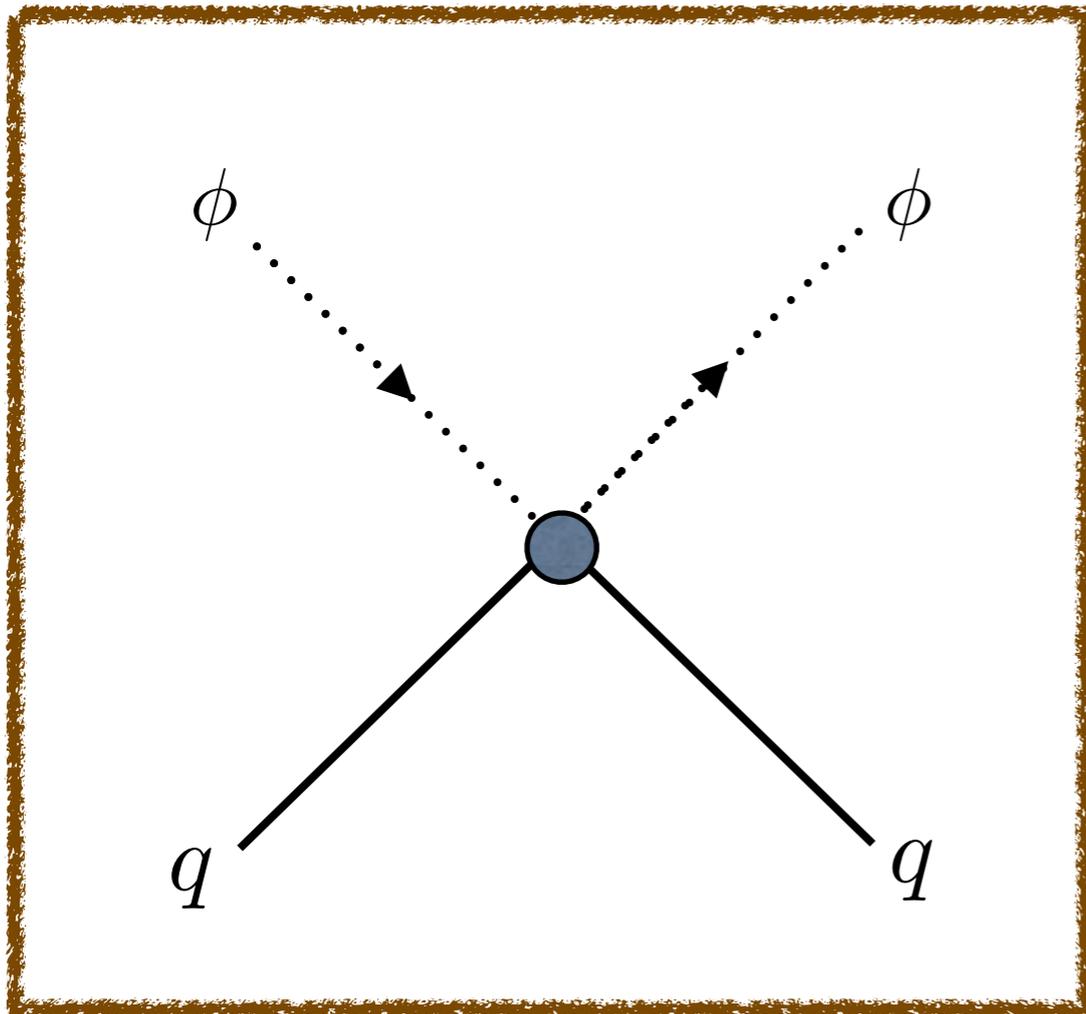
Three questions



How does the direct detection look like?

What kind of models can give this process?

Three questions



dark mediator **D**ark **M**atter

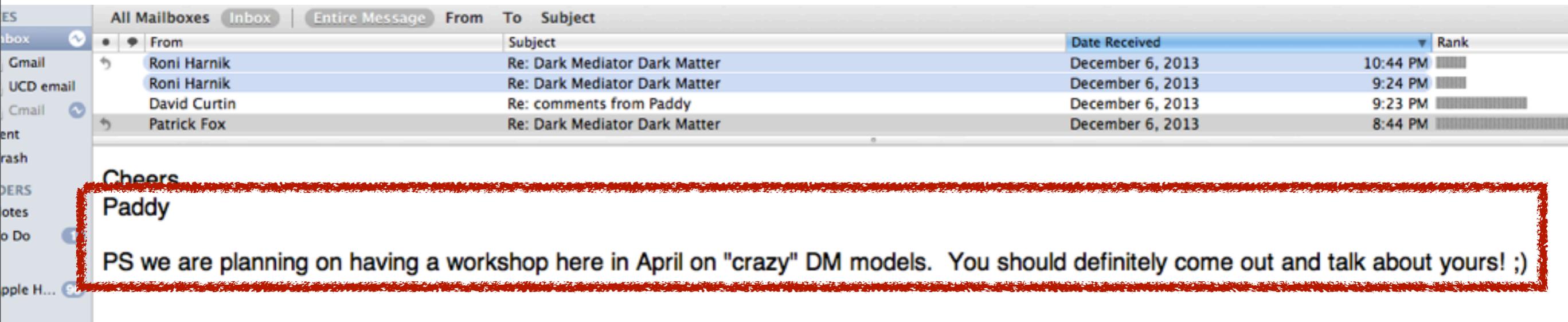
How does the direct detection look like?

What kind of models can give this process?

What is the bound on this light scalar - quark coupling?

David will talk about this

Why talking about crazy DM models?



The screenshot shows an email client interface with a list of emails in the inbox. The selected email is from Paddy, with the subject 'Re: Dark Mediator Dark Matter'. The email content is highlighted with a red border and contains the following text:

Cheers
Paddy
PS we are planning on having a workshop here in April on "crazy" DM models. You should definitely come out and talk about yours! ;)

so, it's not totally our fault...

Why talking about crazy DM models?

The screenshot shows an email client interface. The top part is an inbox table with columns for From, Subject, Date Received, and Rank. Below the table, the message content is visible, including a signature and a postscript (PS) that is highlighted with a red hand-drawn border.

From	Subject	Date Received	Rank
Roni Harnik	Re: Dark Mediator Dark Matter	December 6, 2013	10:44 PM
Roni Harnik	Re: Dark Mediator Dark Matter	December 6, 2013	9:24 PM
David Curtin	Re: comments from Paddy	December 6, 2013	9:23 PM
Patrick Fox	Re: Dark Mediator Dark Matter	December 6, 2013	8:44 PM

Cheers
Paddy

PS we are planning on having a workshop here in April on "crazy" DM models. You should definitely come out and talk about yours! ;)

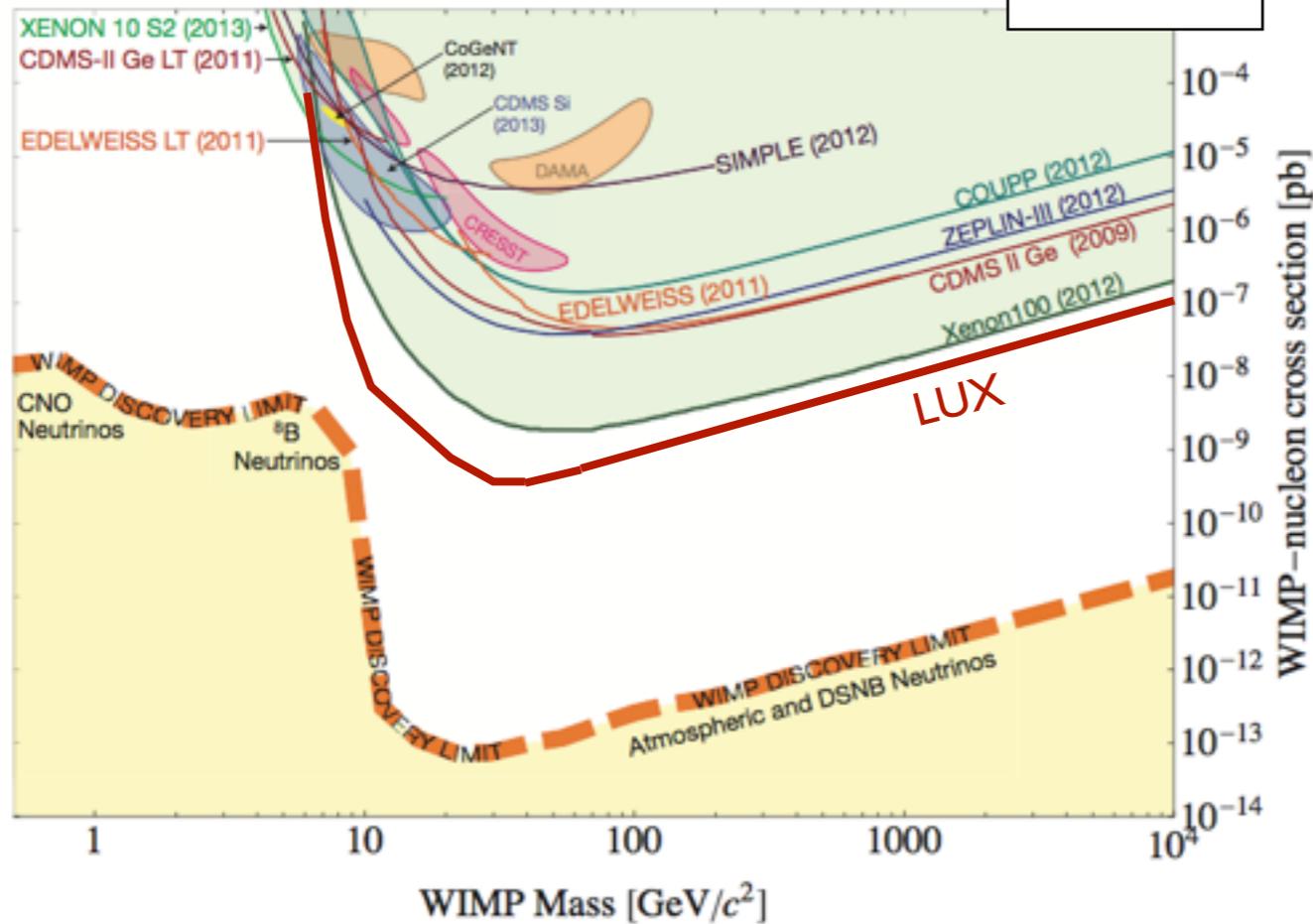
so, it's not totally our fault...

also, our model is not crazier than yours!

Current DM experiments

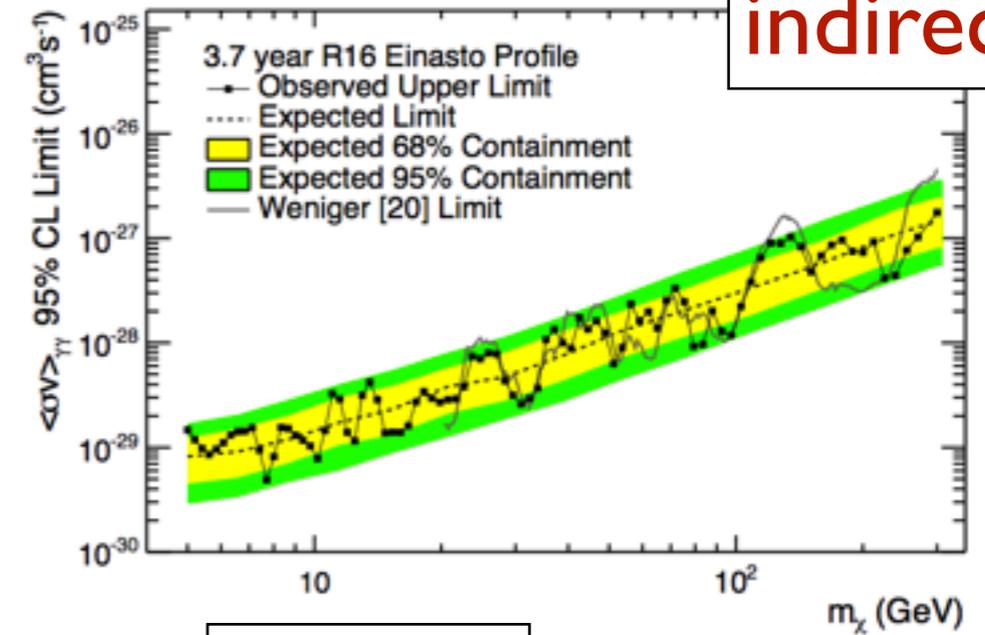
J. Billard and E. Figueroa-Feliciano (13)

direct

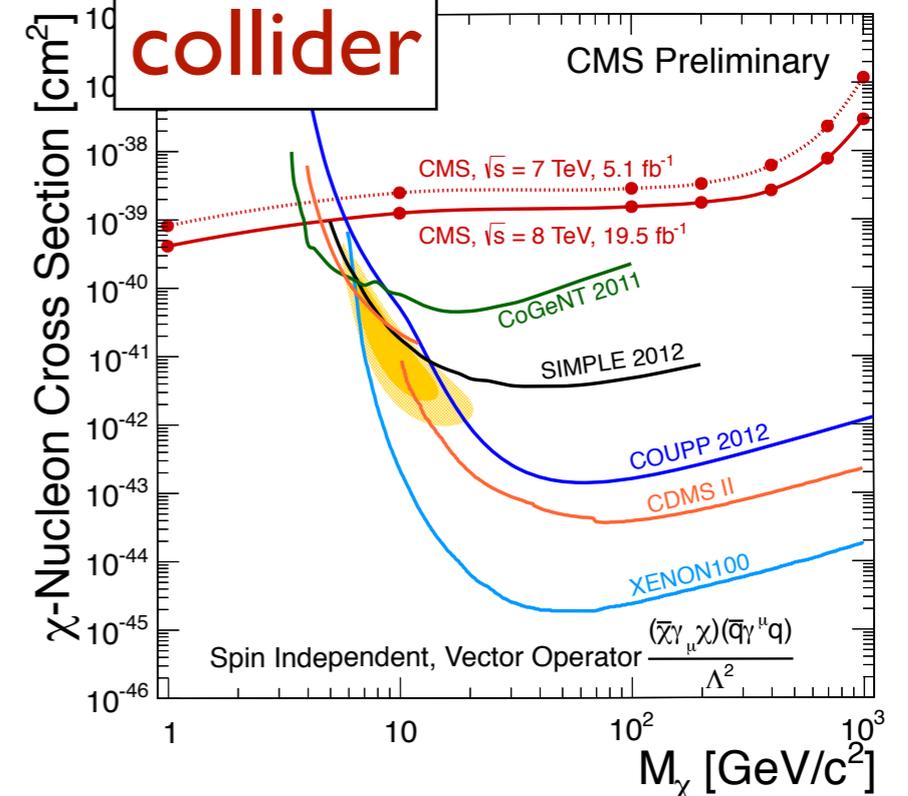


FERMI

indirect



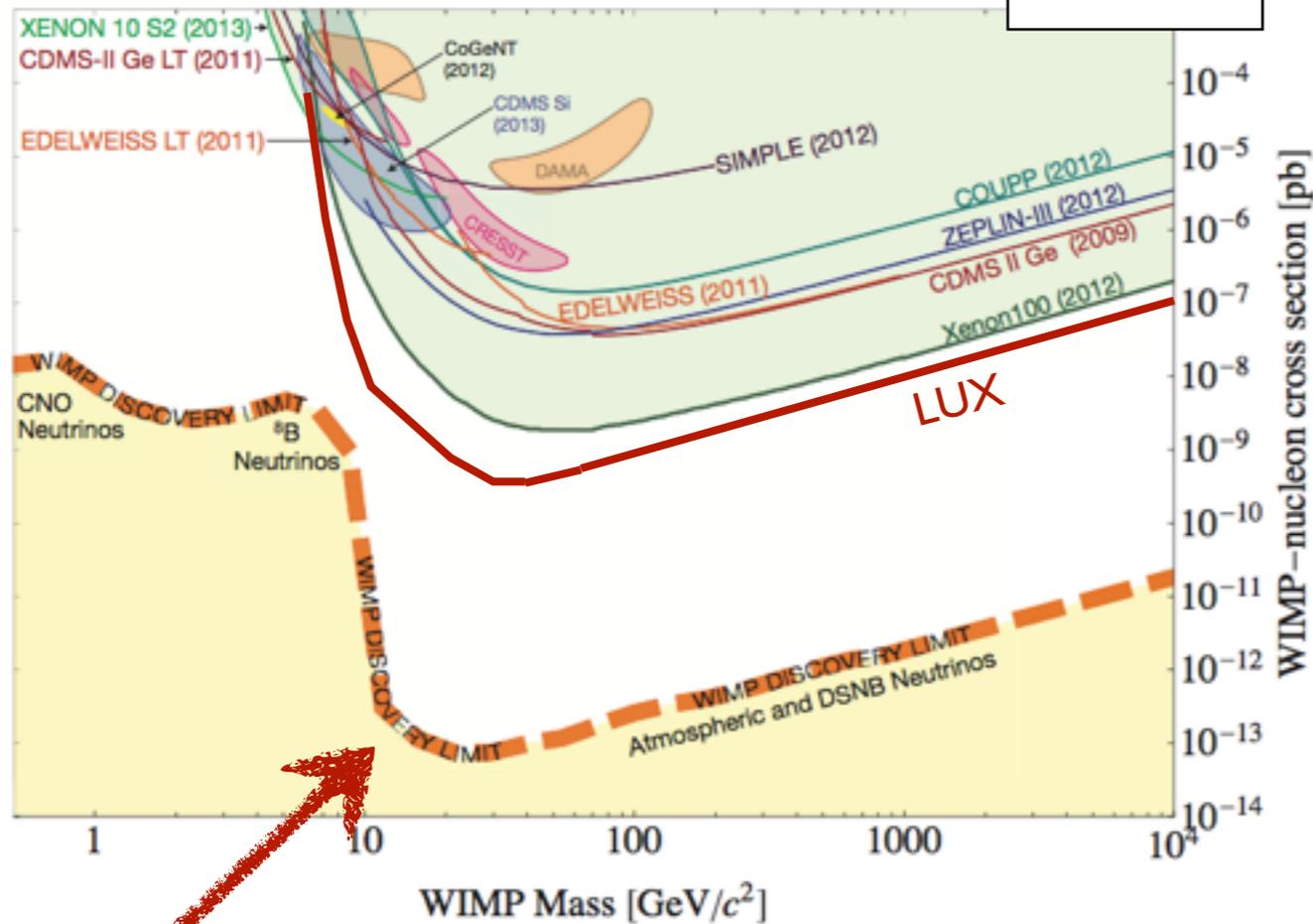
collider



Current DM experiments

J. Billard and E. Figueroa-Feliciano (13)

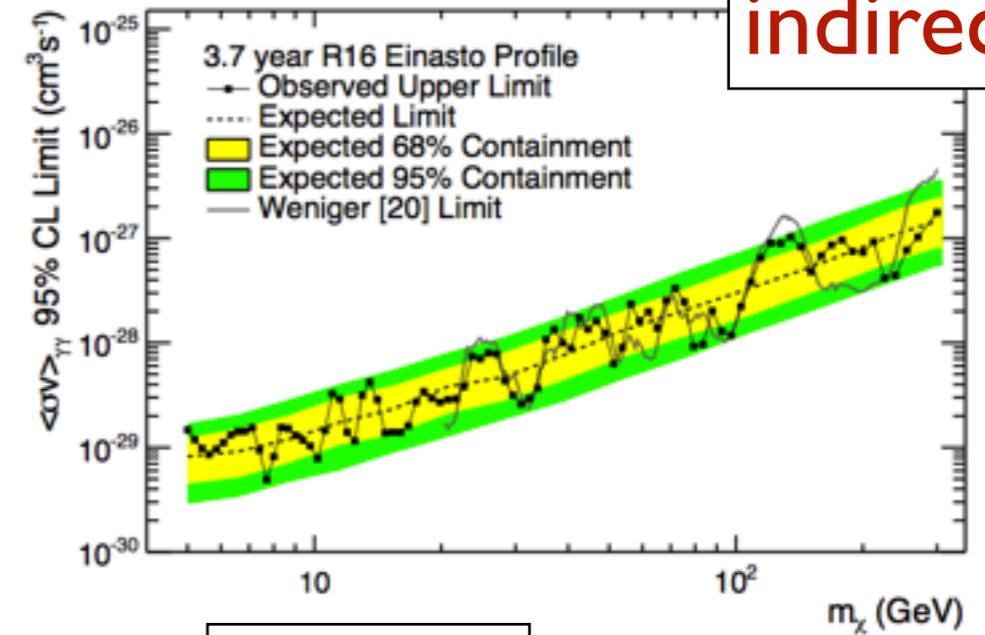
direct



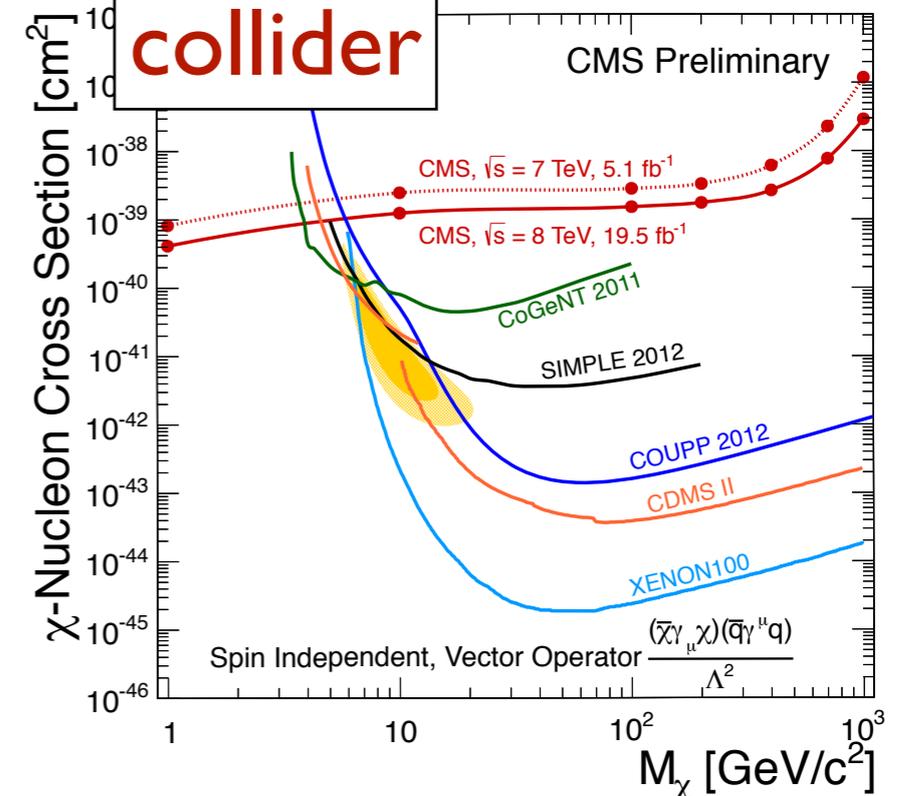
irreducible neutrino-background sets a lower bound on the discovery

FERMI

indirect



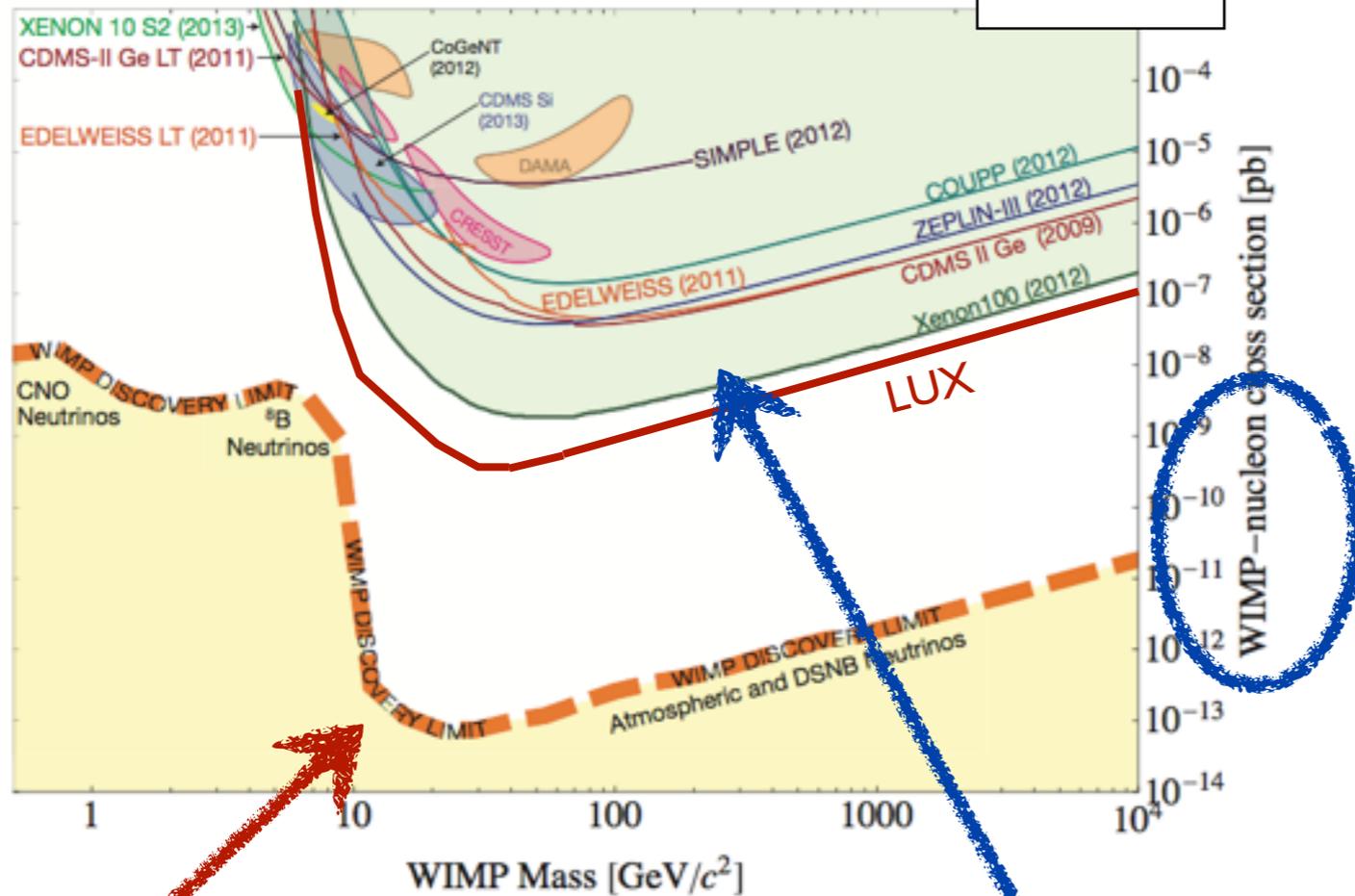
collider



Current DM experiments

J. Billard and E. Figueroa-Feliciano (13)

direct

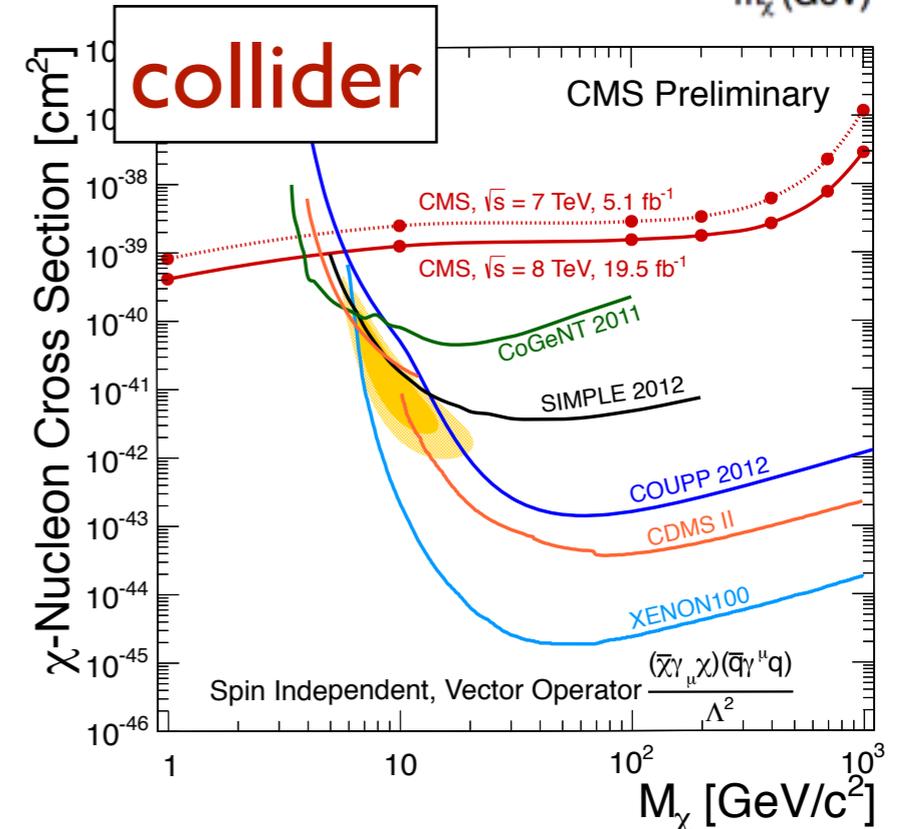
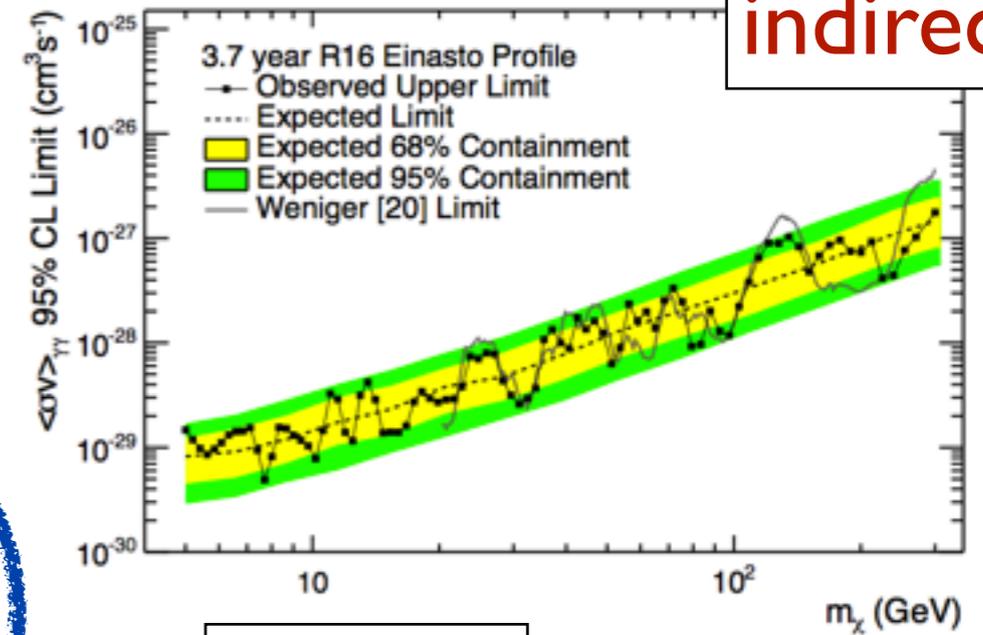


irreducible neutrino-background sets a lower bound on the discovery

assume 2 to 2 scatterings with a contact DM-quark coupling

FERMI

indirect



collider

CMS Preliminary

CMS, $\sqrt{s} = 7$ TeV, 5.1 fb⁻¹

CMS, $\sqrt{s} = 8$ TeV, 19.5 fb⁻¹

CoGeNT 2011

SIMPLE 2012

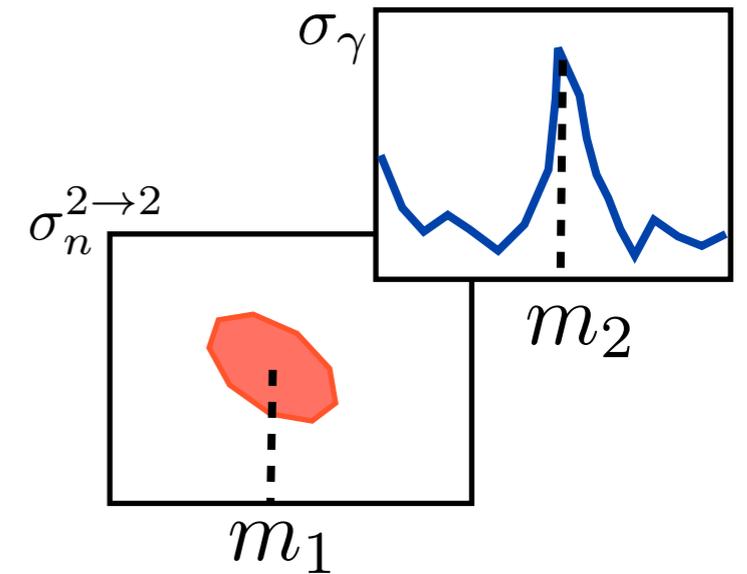
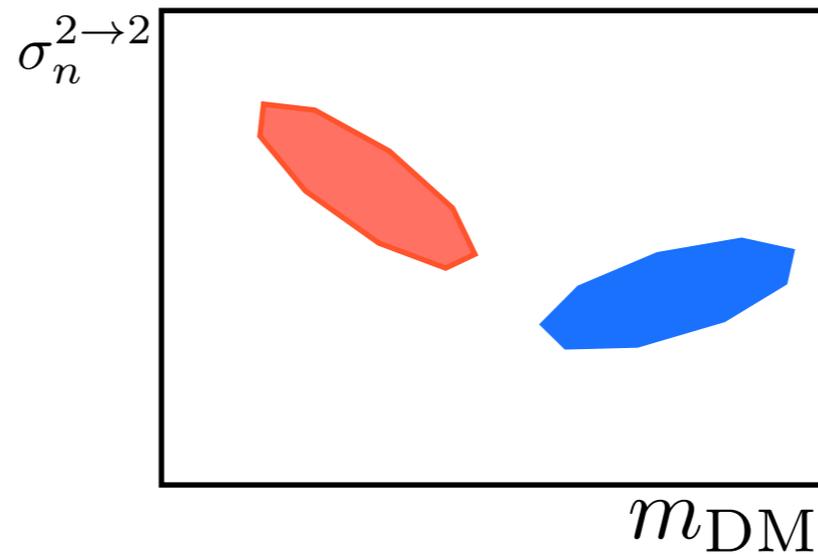
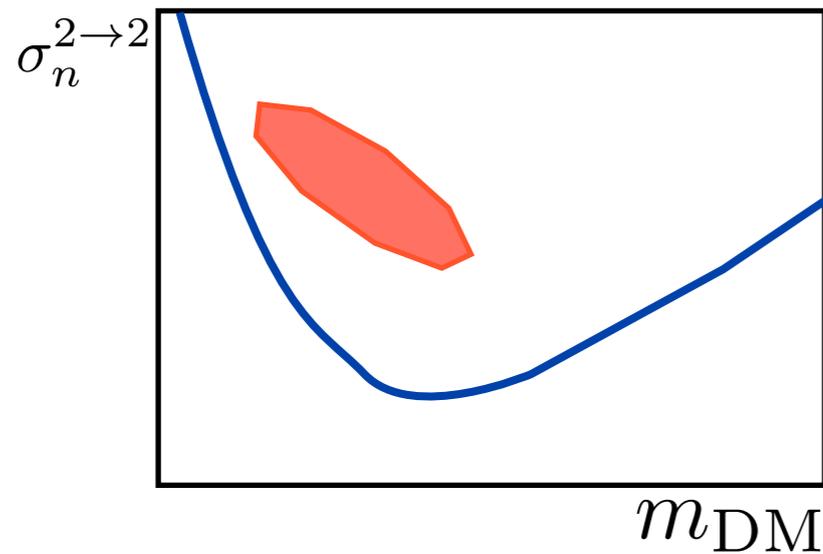
COUPP 2012

CDMS II

XENON100

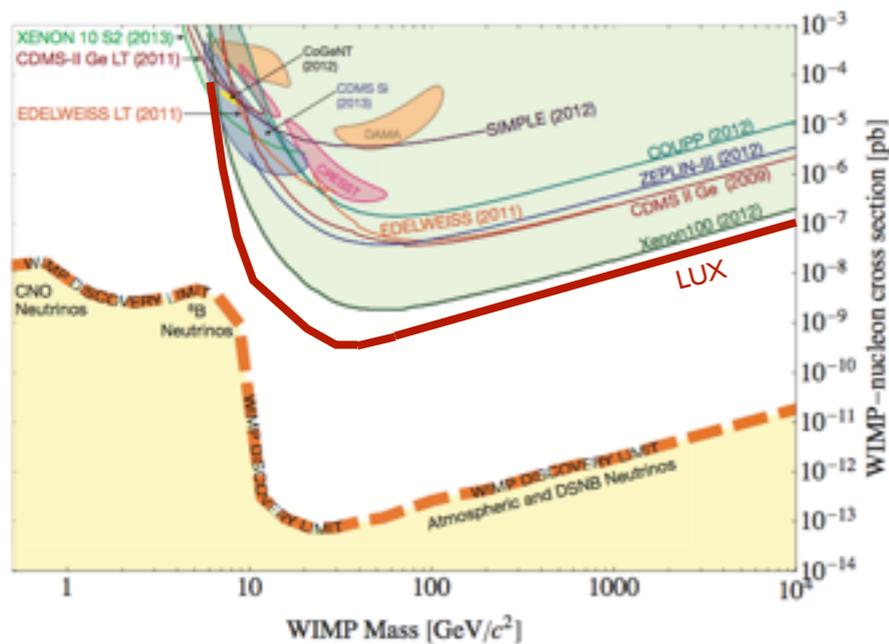
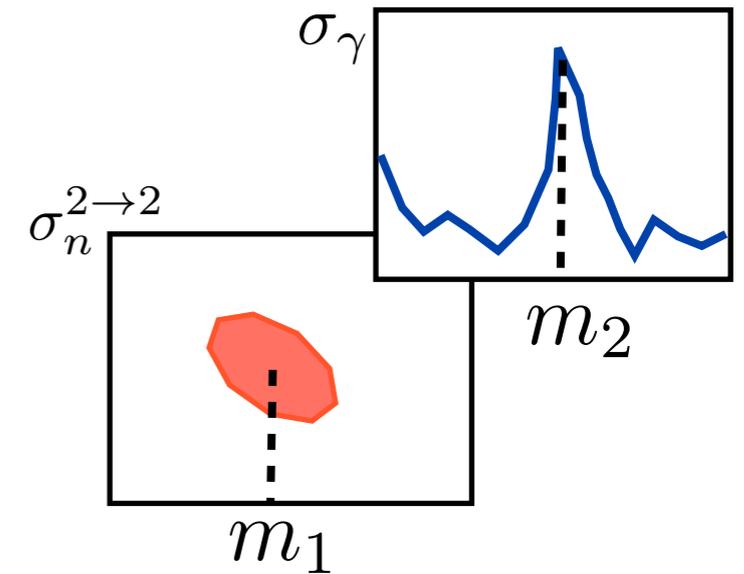
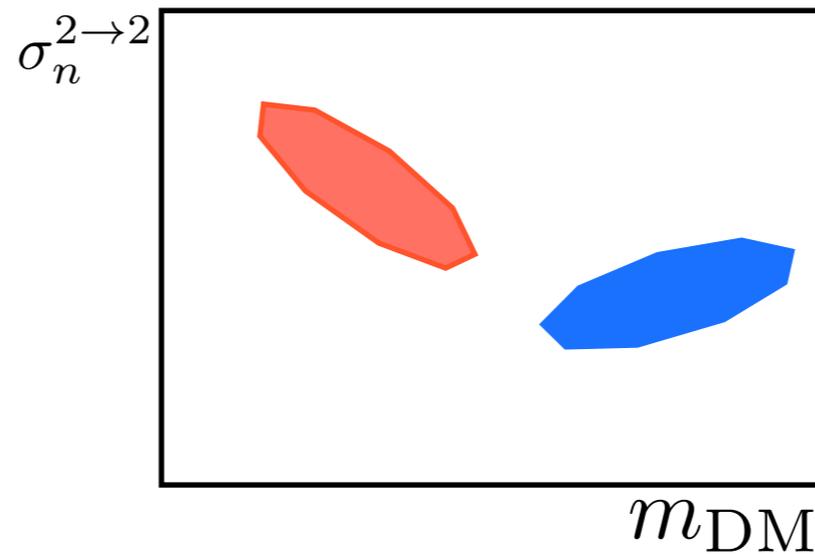
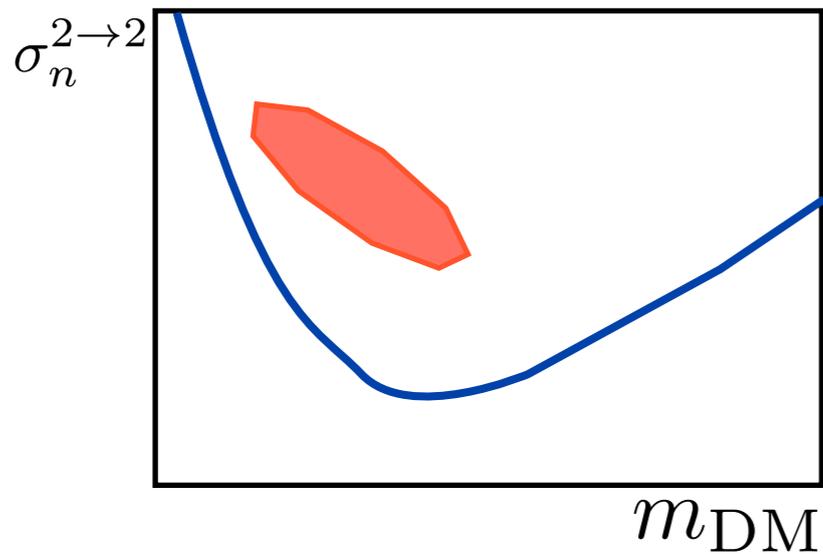
Spin Independent, Vector Operator $\frac{(\bar{\chi}\gamma_{\mu}\chi)(\bar{q}\gamma^{\mu}q)}{\Lambda^2}$

Useful inconsistencies



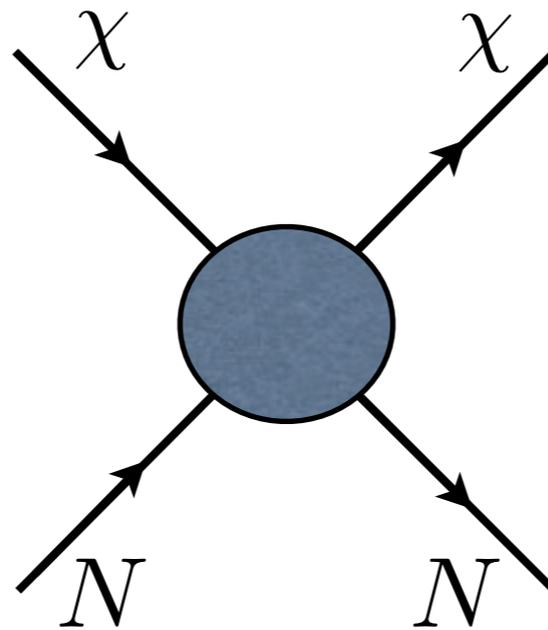
The inconsistencies between different experiments may reflect the detailed structure of the dark sector

Useful inconsistencies



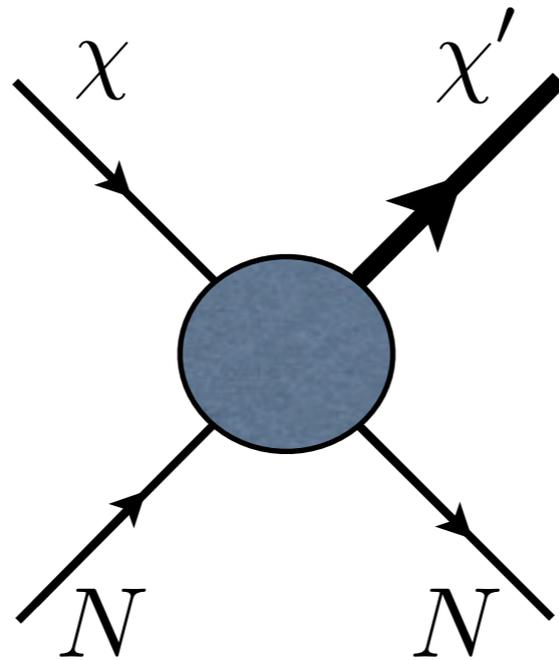
It is important to explore a complete set of DM models that may can different future signals

Beyond WIMP-like scattering



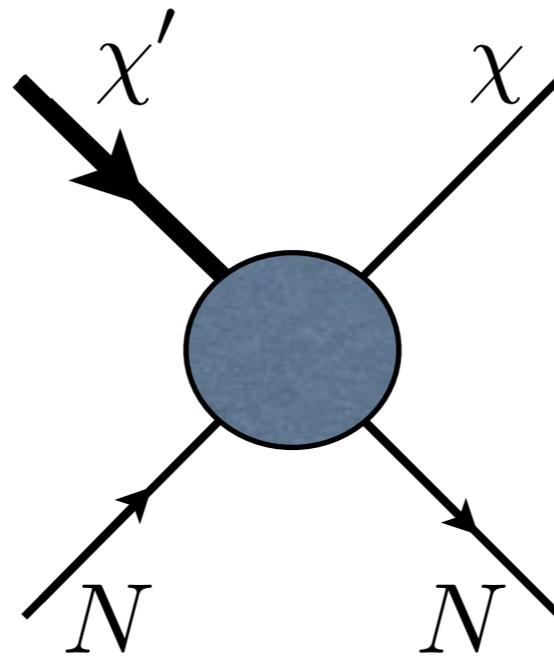
looking for simple extension of the model
that changes the recoil spectrum

Beyond WIMP-like scattering



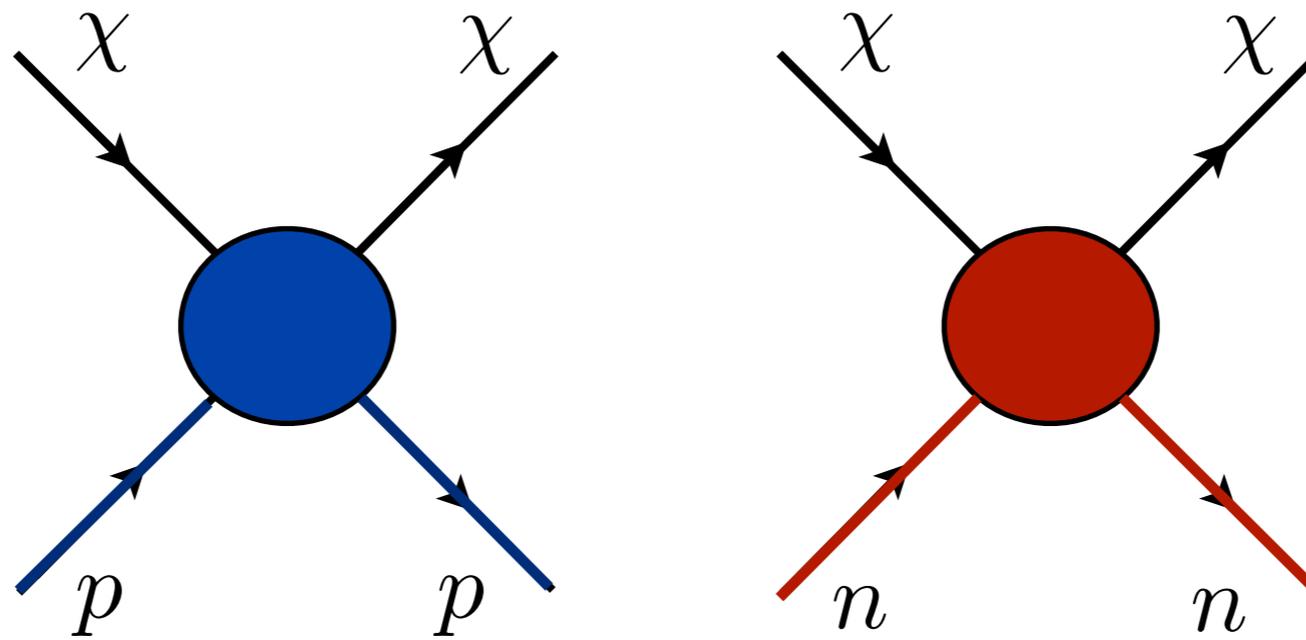
Inelastic DM

Beyond WIMP-like scattering



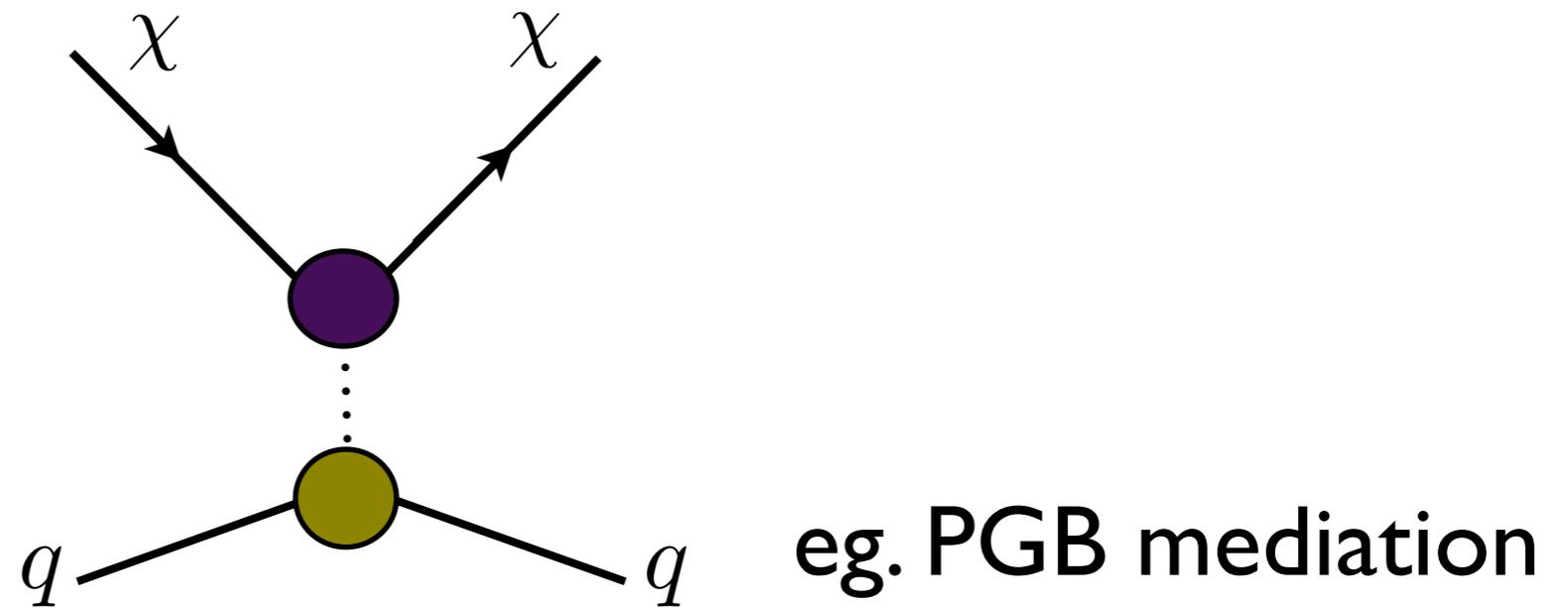
Exothermic DM

Beyond WIMP-like scattering



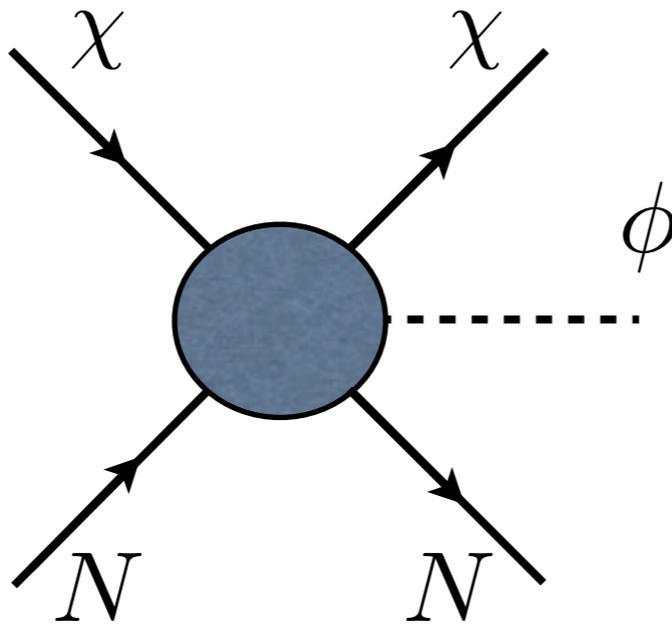
Isospin violation

Beyond WIMP-like scattering



different type of couplings & mediators

One missing ingredient

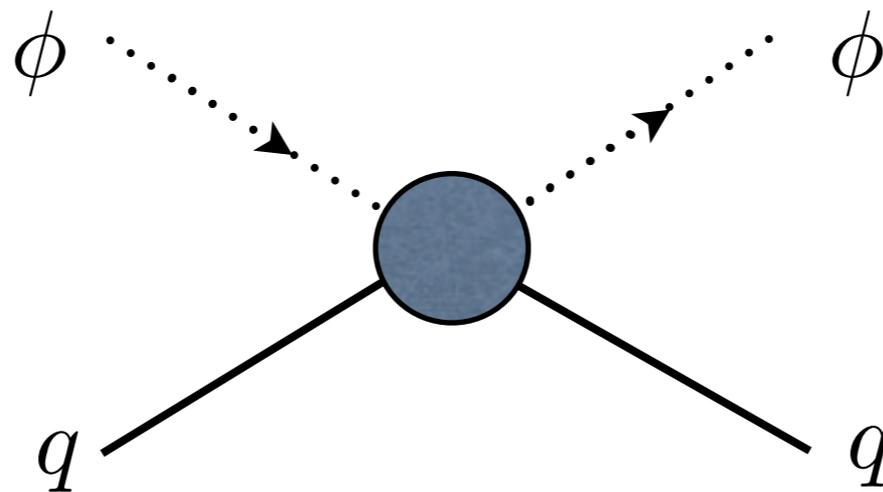


different scattering topology

changes recoil spectrum and mass measurement

A model building motivation

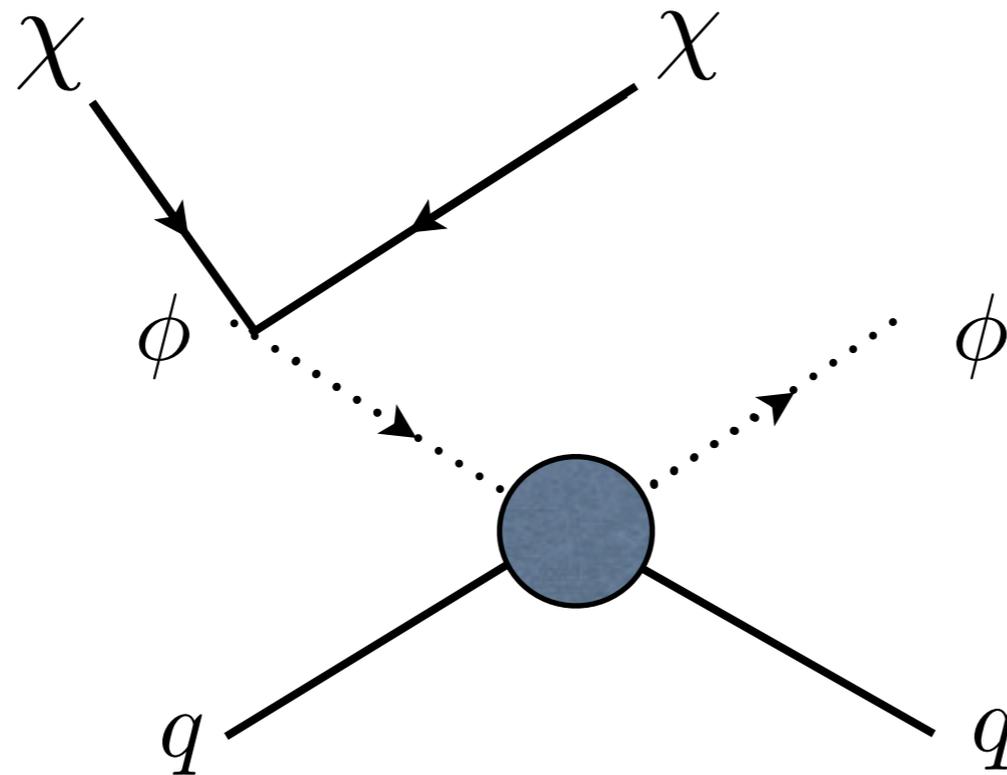
What if the mediator itself carries a dark charge?



dark mediator Dark Matter

A model building motivation

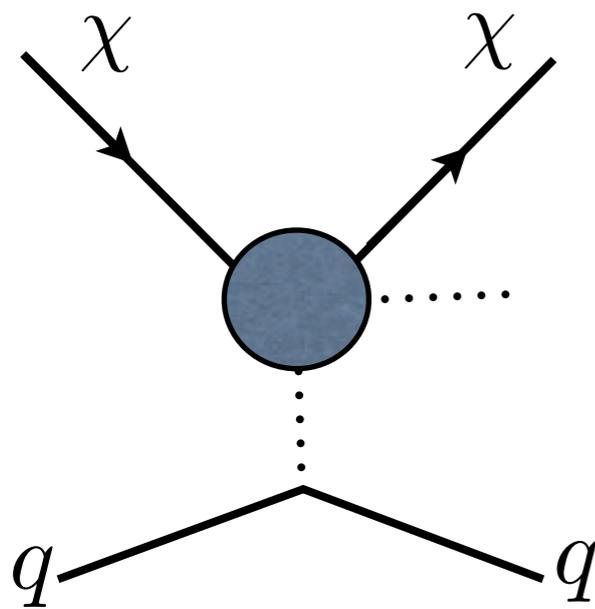
What if the mediator itself carries a dark charge?



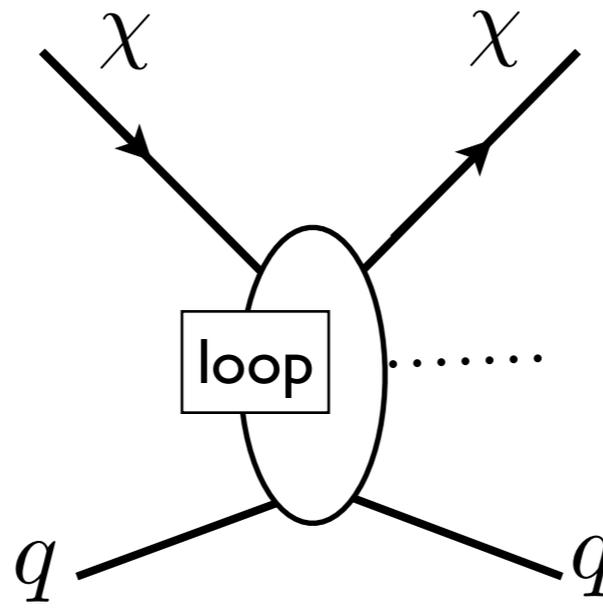
dark mediator Dark Matter

It is a natural way to obtain a 2 to 3 scattering

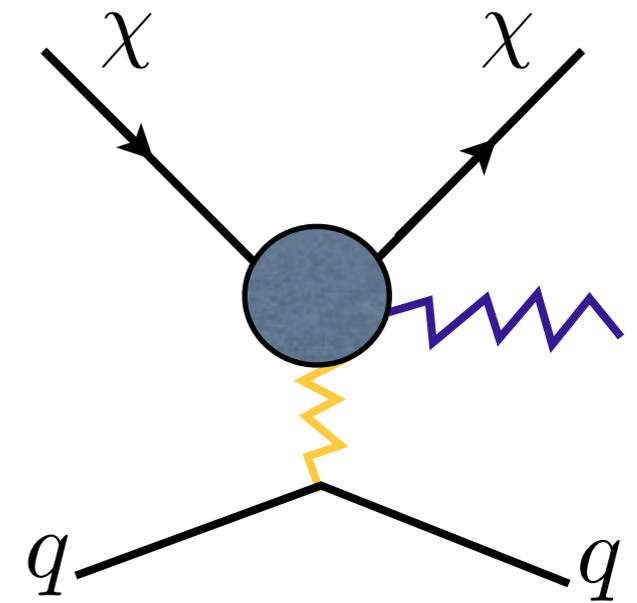
It's not easy to write down a viable model giving 2to3 scattering



strong bounds on light singlet scalars. hard to avoid the 2 to 2 scattering



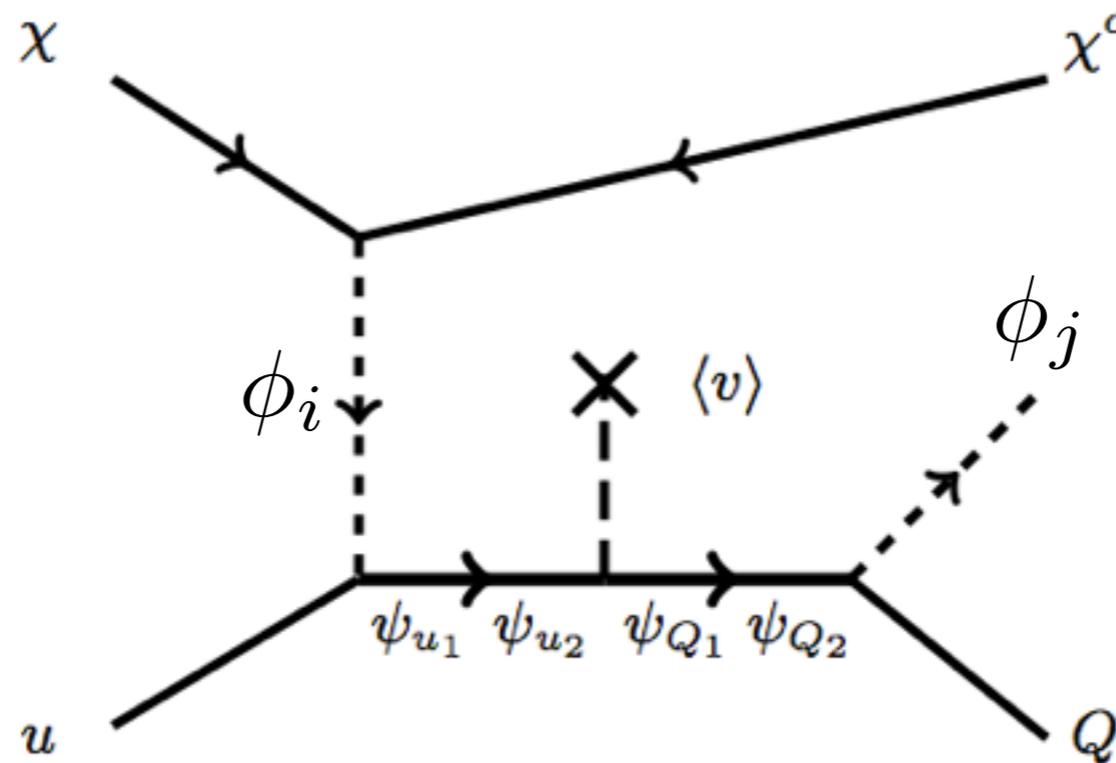
the loop suppression makes it hard to have a large cross section



derivative couplings give velocity suppressions, assume DM doesn't carry SM charges

Focus on the dmDM in this talk

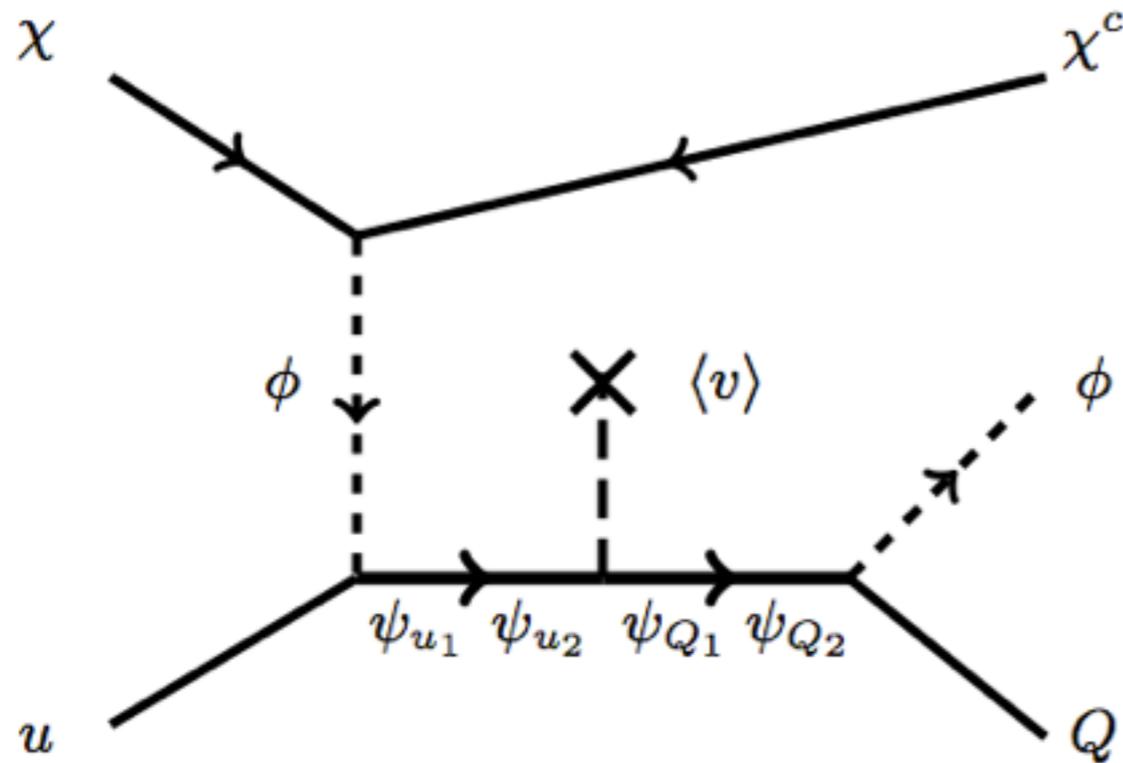
One example : vectorized quarks



$$\supset \frac{\phi_i \phi_j \bar{Q} q}{\Lambda_{ij}} + y_\chi^i \bar{\chi}^c \chi \phi_i + h.c.$$

2 to 3 exists as long as $m_{\phi_j} < 10 \text{ keV}$

Minimal model with a single scalar



	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	Z_3
\bar{Q}	$\bar{3}$	$\bar{2}$	$-1/6$	0
u	3	1	$2/3$	0
d	3	1	$-1/3$	0
H	1	2	$1/2$	0
ϕ	1	1	0	$2\pi/3$
$\psi_{Q_{1,2}}$	3	2	$1/6$	$2\pi/3$
$\psi_{u_{1,2}}$	3	1	$2/3$	$2\pi/3$
$\psi_{d_{1,2}}$	3	1	$-1/3$	$2\pi/3$
χ	1	1	0	$2\pi/3$

$$\supset \frac{|\phi|^2 \bar{Q} q}{\Lambda} + y_\chi \bar{\chi}^c \chi \phi + h.c. \quad \Lambda = \frac{M_Q^2}{y_Q y_q y_{Qq} v}$$

- assume $y_Q = y_q = y_{Qq} = 1$ in the quark mass basis for simplicity
- assume the effective scalar-quark coupling is flavor universal in the mass basis

Direct detection of dmDM



Direct detection in MadGraph



To obtain the recoil spectrum

- generate the DM-quark scattering using **MadGraph5**
- multiply the cross section with the **nuclear form factor**
- convolute the result with **velocity distribution** and **Helm Form Factor**

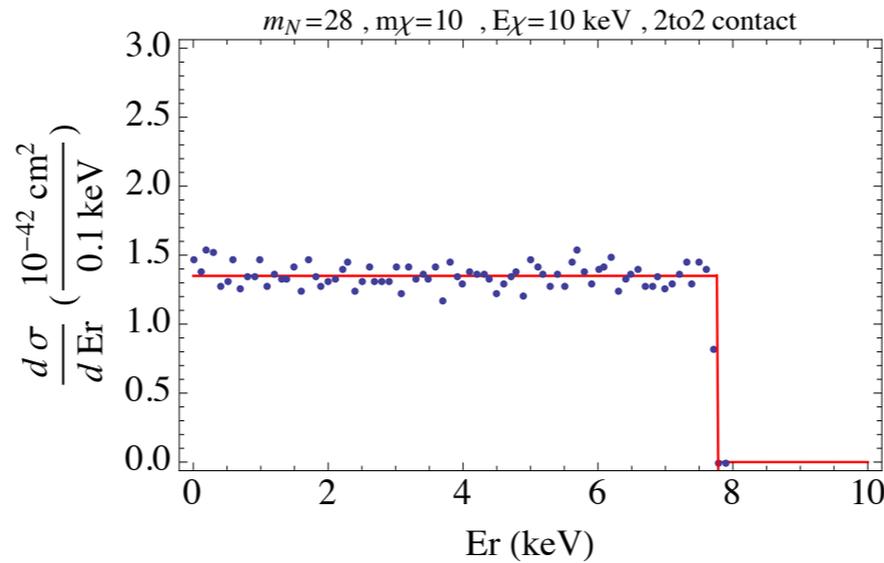
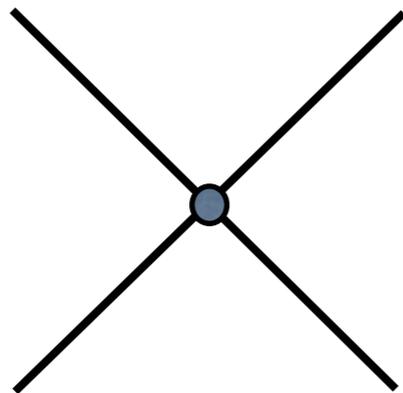
for 2 to 2 contact operator

$$\frac{dR}{dE_r} = N_T \frac{\rho_\chi}{m_\chi} \int dv v f(v) \frac{d\sigma_N}{dE_r} \longrightarrow \frac{dR}{dE_r} = \frac{1}{2} \frac{\sigma_n^{\text{SI}}}{\mu_{n\chi}^2} N_T \rho_\chi \frac{m_N}{m_\chi} A^2 F^2(E_r) \int_{v_{\min}(E_r)}^{v_{\max}} dv \frac{1}{v} f(v)$$

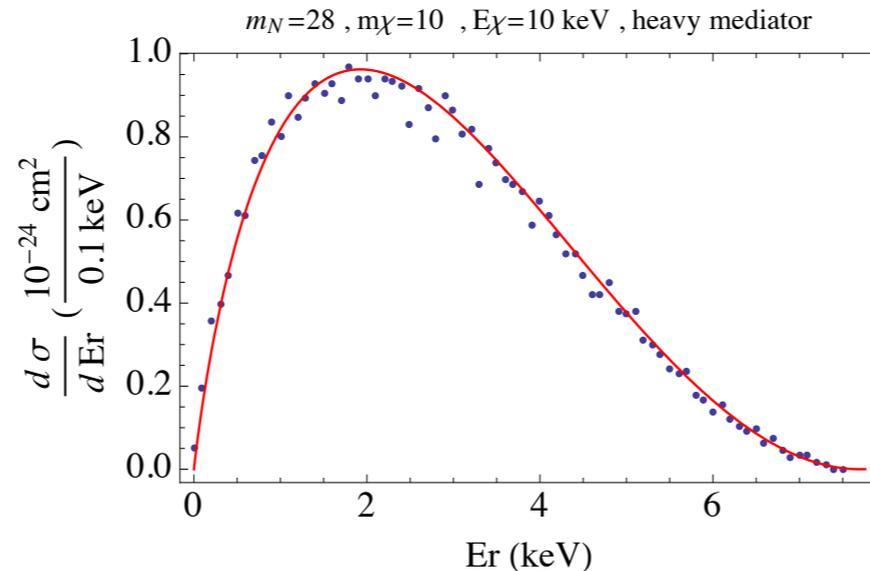
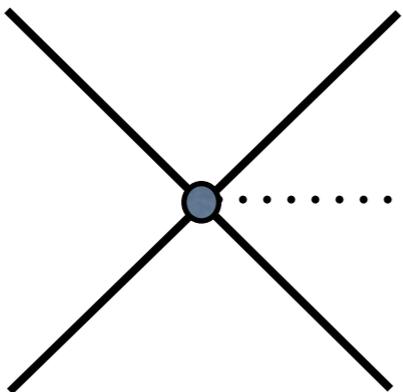
Recoil Spectrum

For a given DM energy

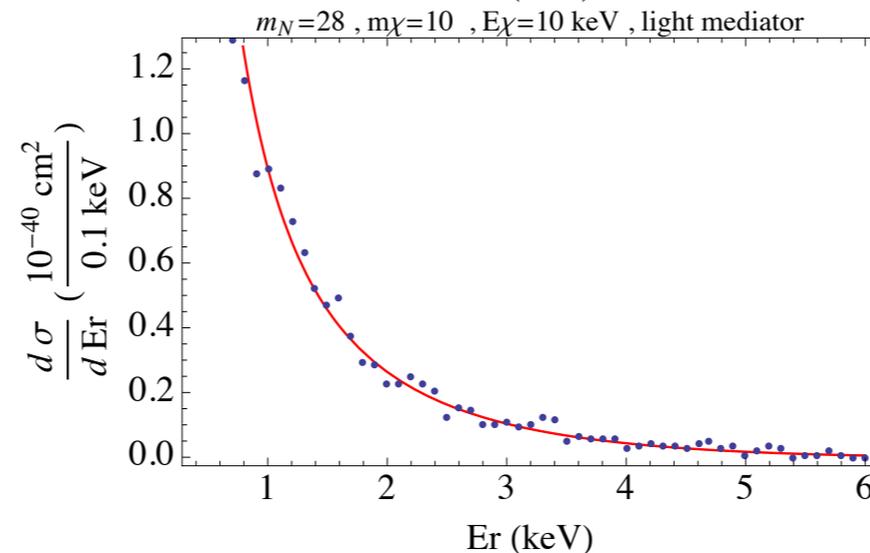
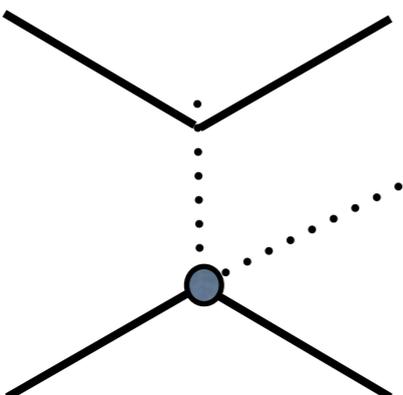
standard 2 to 2
contact operator



2 to 3
contact operator



2 to 3
light mediator



$$\frac{d\sigma}{dE_R} = \frac{|\mathcal{M}|^2}{32\pi m_\chi^2 m_N v^2}$$

$$|\mathcal{M}|^2 \propto \frac{m_N^2 m_\chi^2}{\Lambda^4}$$

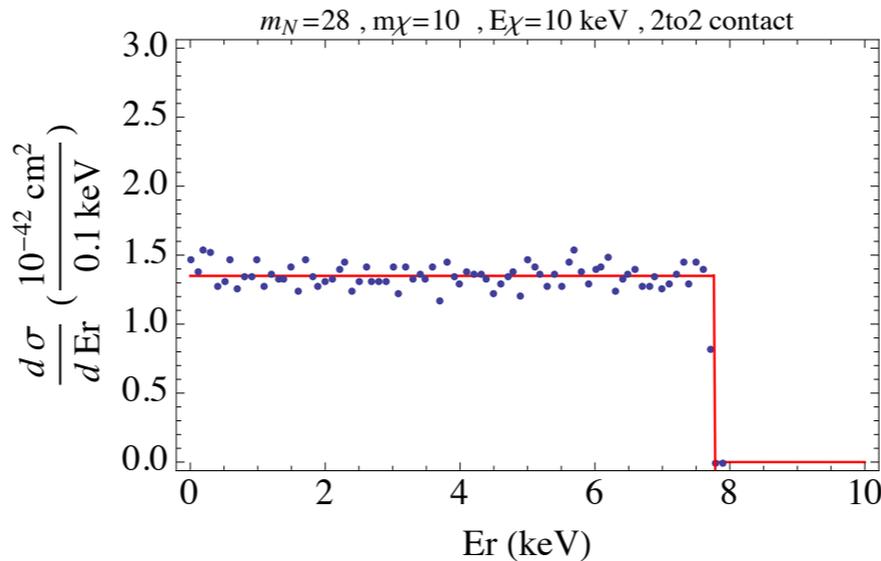
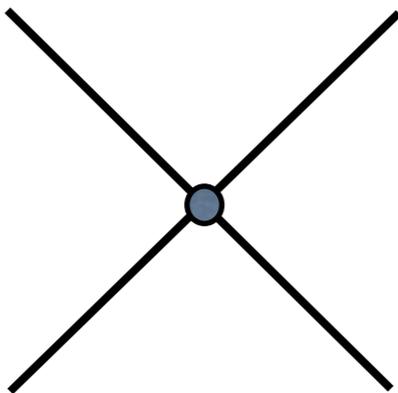
for $\frac{\bar{\chi}\chi\bar{q}q}{\Lambda^2}$ $\frac{\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q}{\Lambda^2}$

$$E_r^{max} = \frac{2\mu_{N\chi}^2 v^2}{m_N}$$

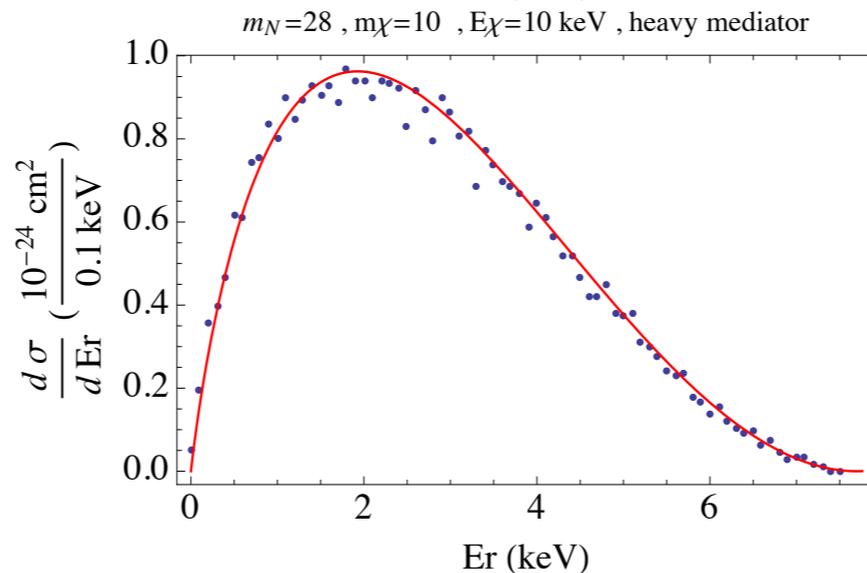
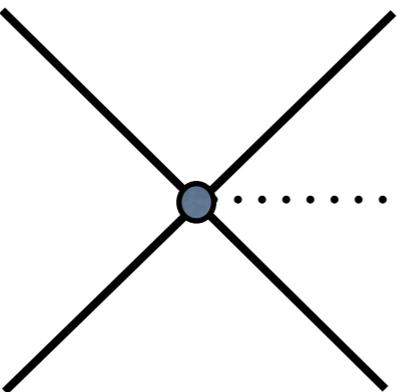
Recoil Spectrum

For a given DM energy

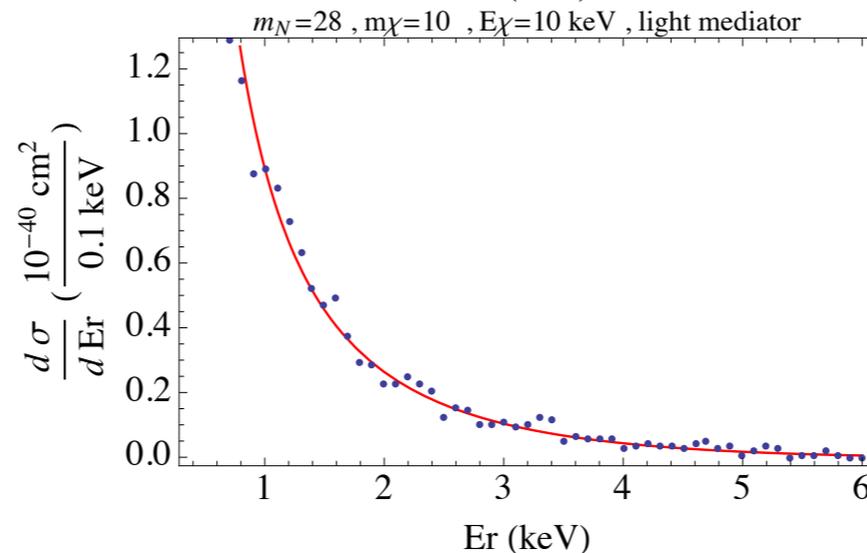
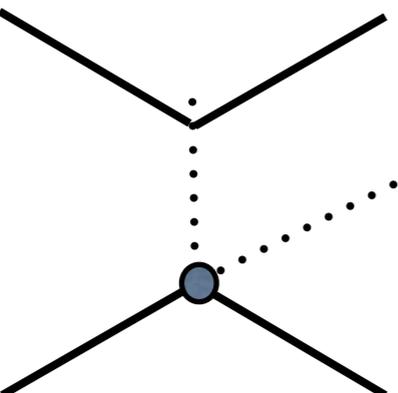
standard 2 to 2
contact operator



2 to 3
contact operator



2 to 3
light mediator



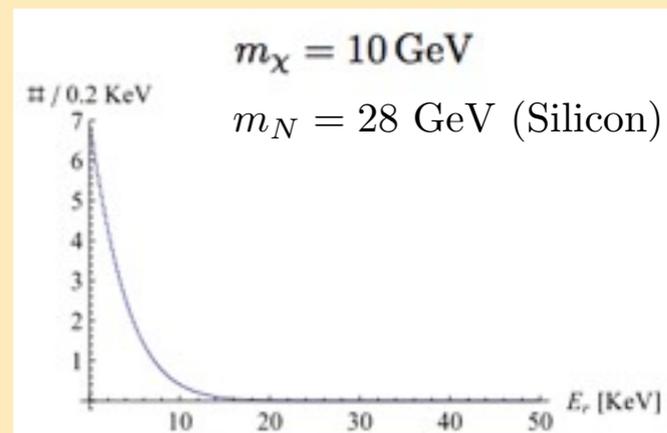
$$\frac{d\sigma}{dE_R} = \frac{|\mathcal{M}|^2}{32\pi m_\chi^2 m_N v^2}$$

$$|\mathcal{M}|^2 \propto \frac{m_N^2 m_\chi^2}{\Lambda^4}$$

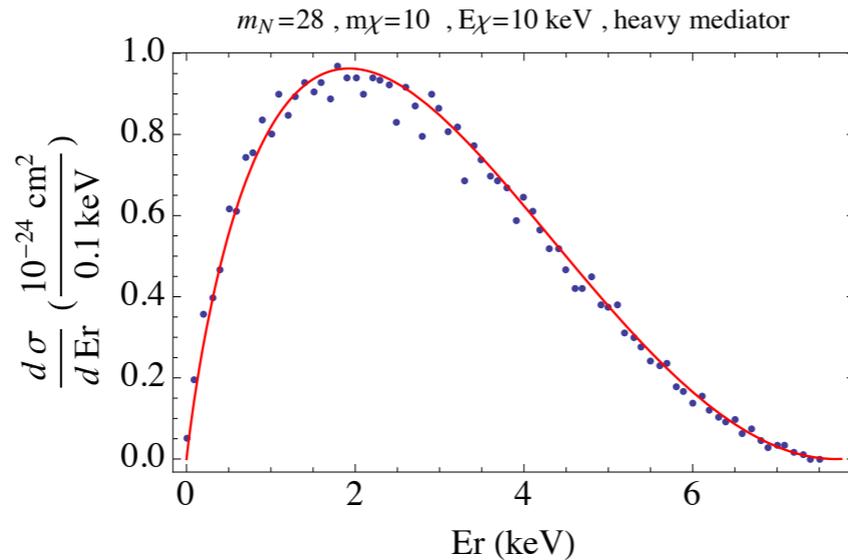
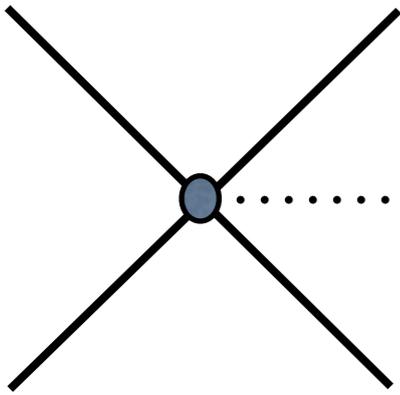
for $\frac{\bar{\chi}\chi\bar{q}q}{\Lambda^2}$ $\frac{\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q}{\Lambda^2}$

$$E_r^{max} = \frac{2\mu_{N\chi}^2 v^2}{m_N}$$

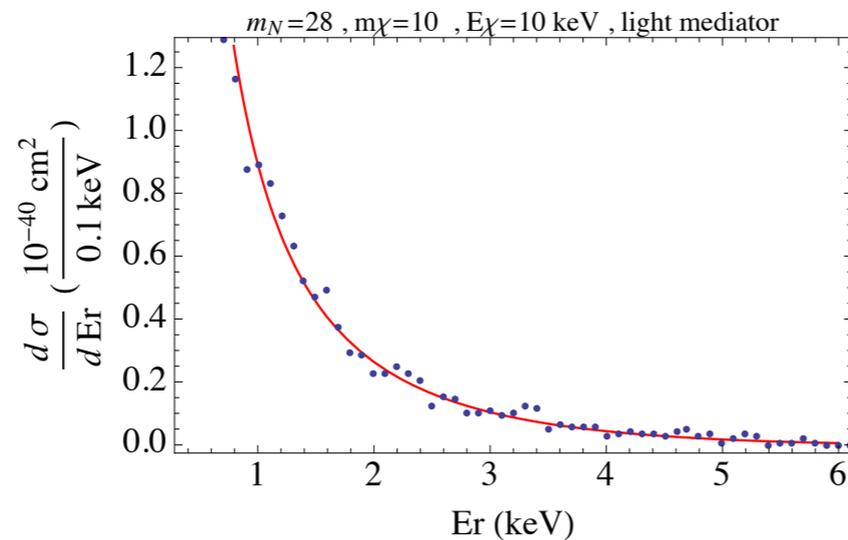
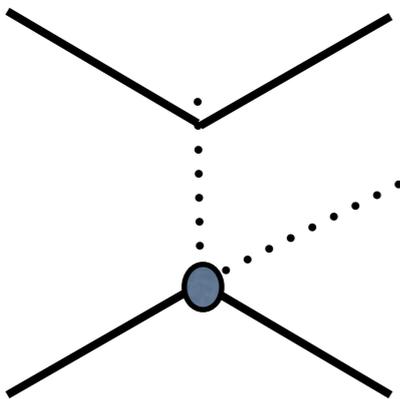
2to2 after f(ν) and F



Recoil Spectrum



$$\propto m_N^2 E_R \left(1 - \sqrt{E_R/E_R^{max}} \right)^2$$

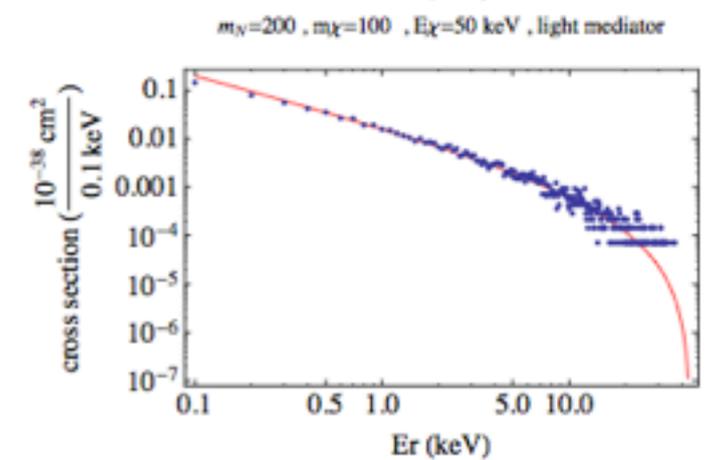
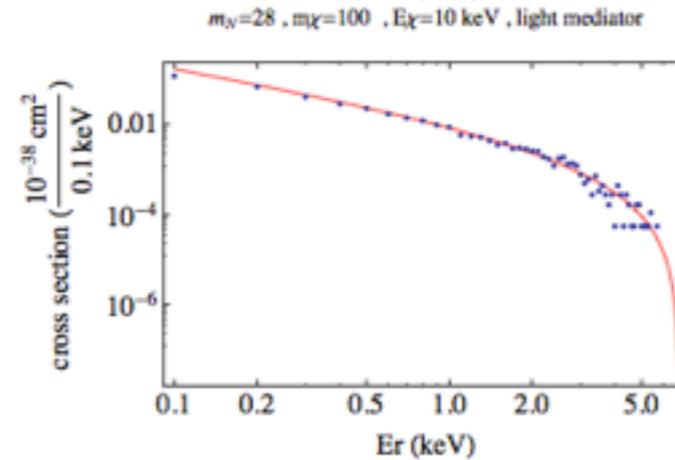
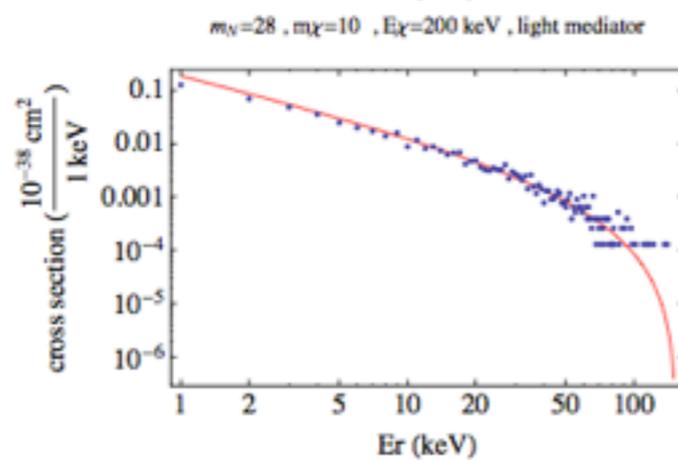
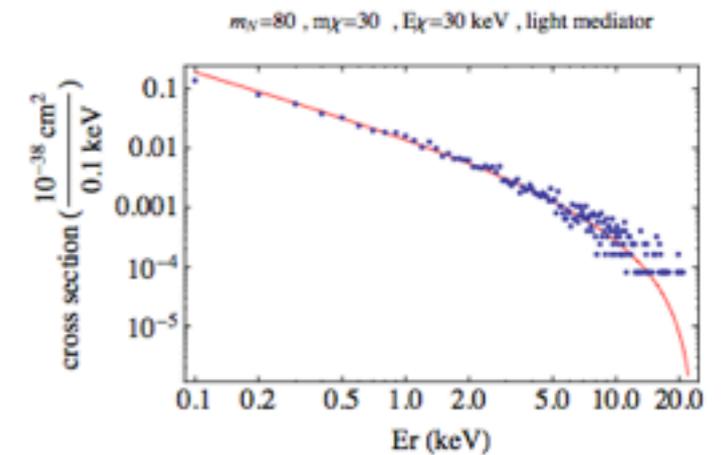
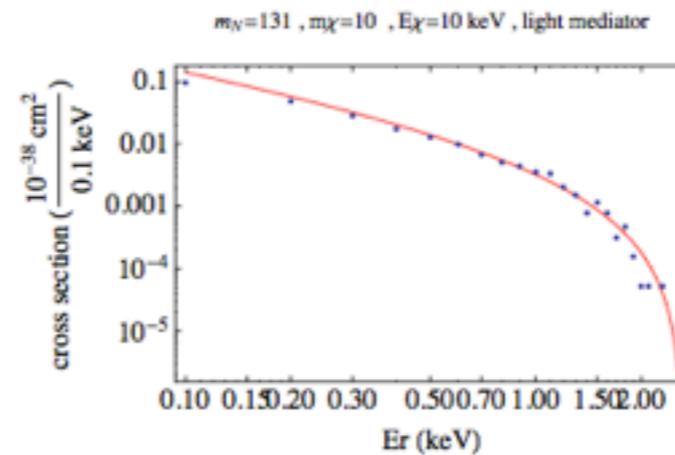
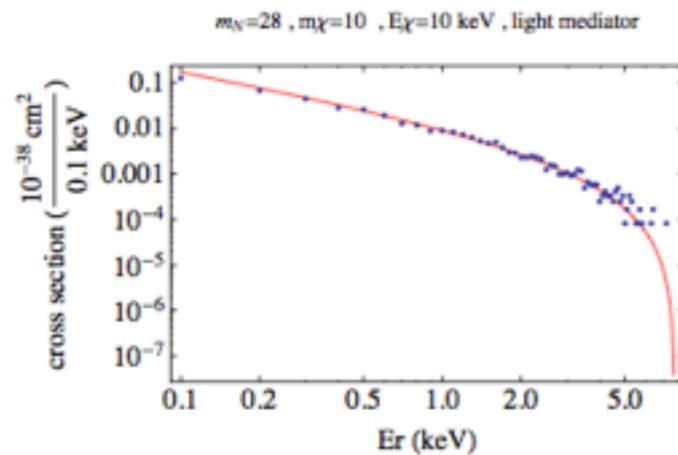
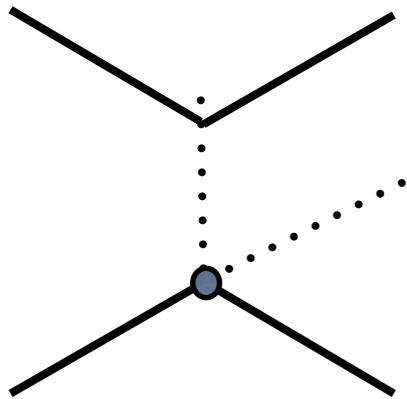


$$\propto E_R^{-1} \left(1 - \sqrt{E_R/E_R^{max}} \right)^2$$

with $E_R^{max} = \frac{\mu_{\chi N}^2}{2 m_N} v^2$

Recoil Spectrum

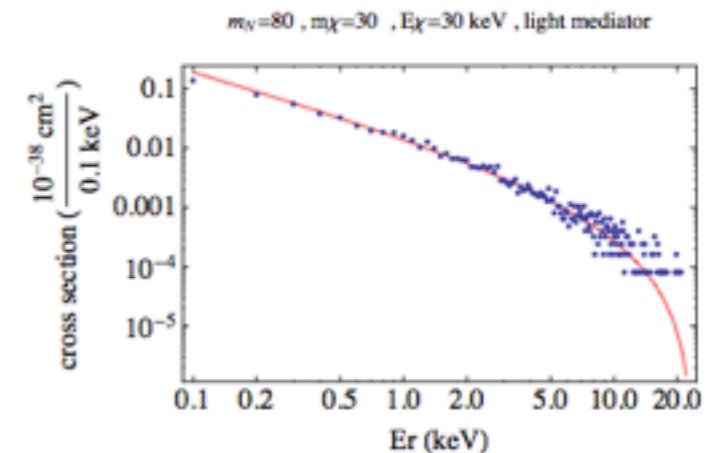
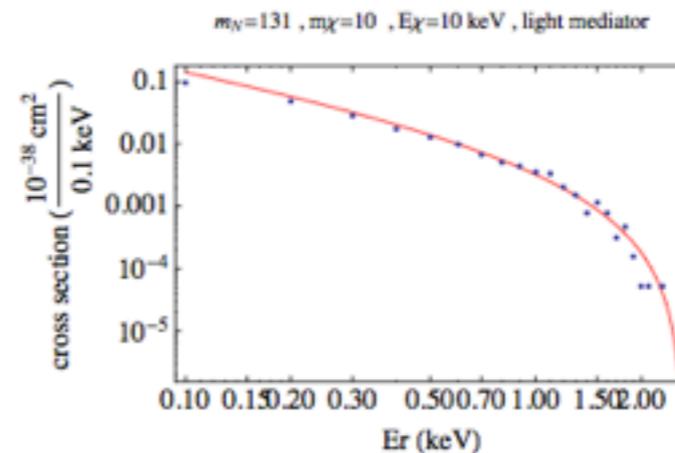
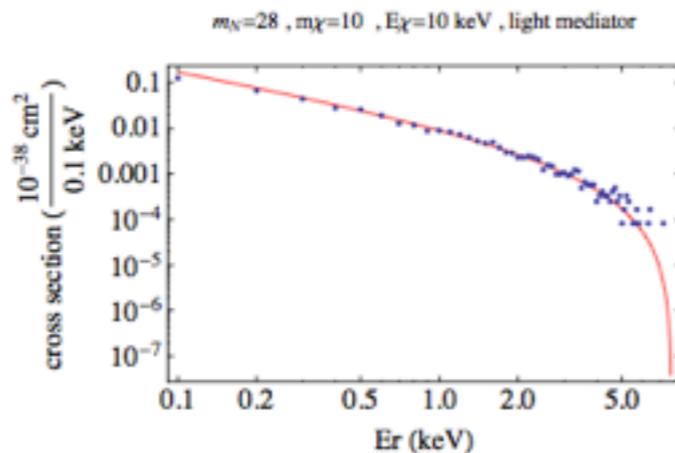
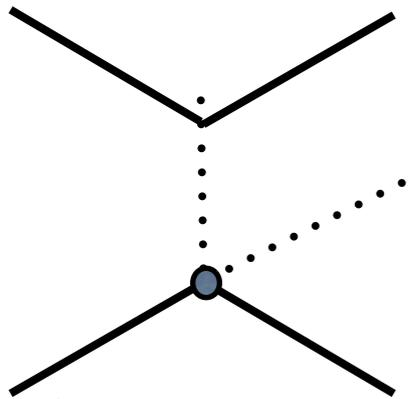
$$\frac{d\sigma_{2\rightarrow 3}^{light}}{dE_R} \simeq constant \times \left(\frac{E_R}{\text{keV}}\right)^{-1} \left(1 - \sqrt{E_R / E_R^{max}}\right)^2, \quad E_R^{max} = 2 \frac{\mu_{\chi N}^2}{m_N} v^2$$



Recoil Spectrum

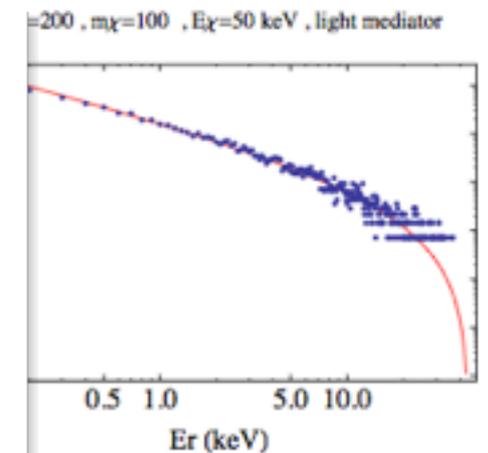
$$\frac{d\sigma_{2\rightarrow 3}^{light}}{dE_R} \simeq constant \times \left(\frac{E_R}{\text{keV}}\right)^{-1} \left(1 - \sqrt{E_R/E_R^{max}}\right)^2,$$

$$E_R^{max} = 2 \frac{\mu_{\chi N}^2}{m_N} v^2$$

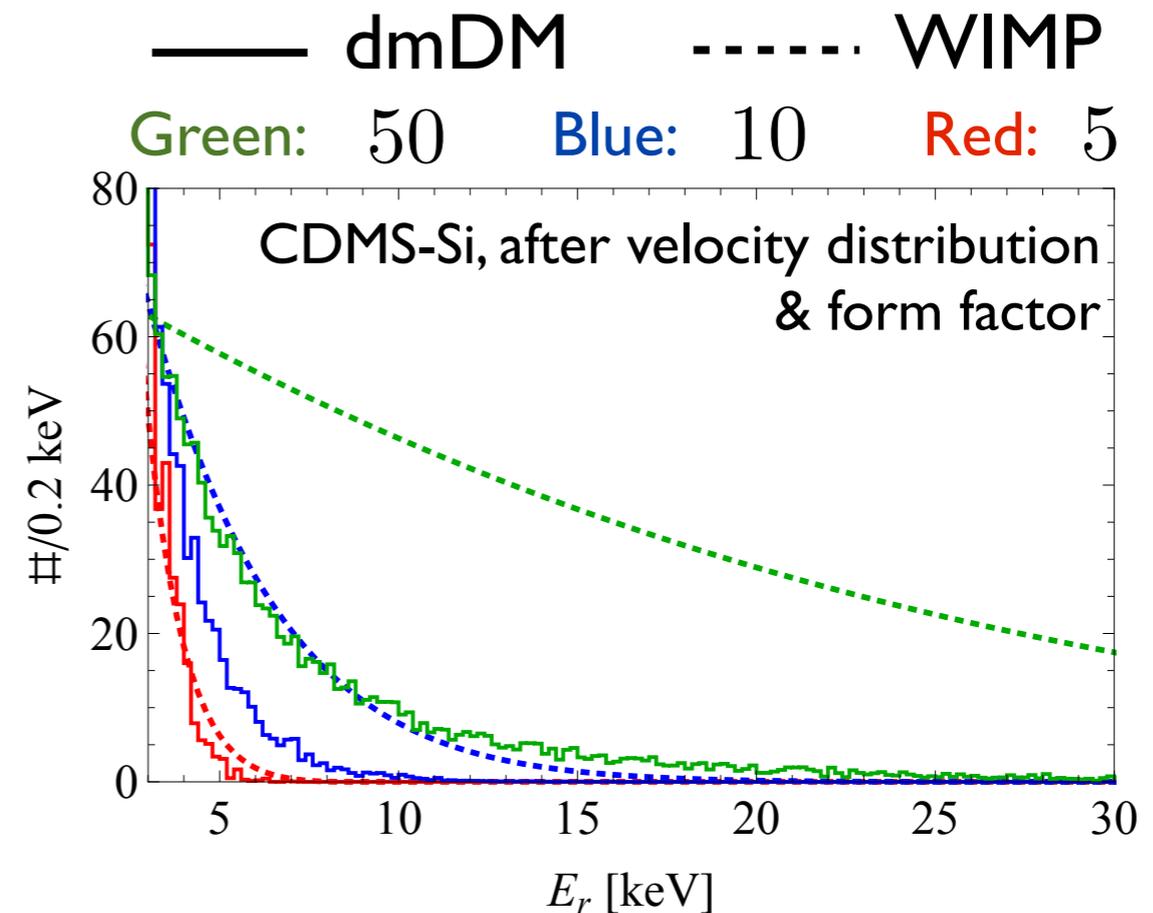
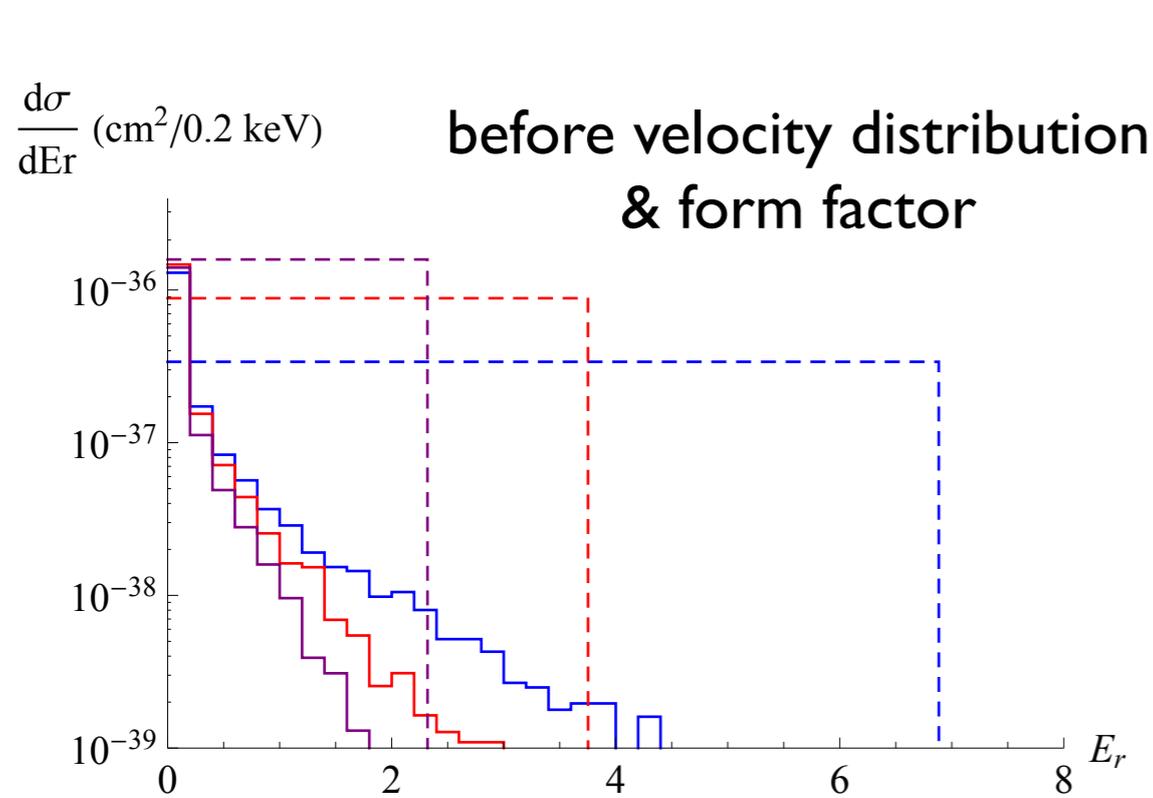


Three ingredients give the spectrum

- I. phase space with ϕ carrying away some energy
- II. E_R^{max} relates to the DM-nucleus mass
- III. E_R^{-2} from the propagator of light mediator

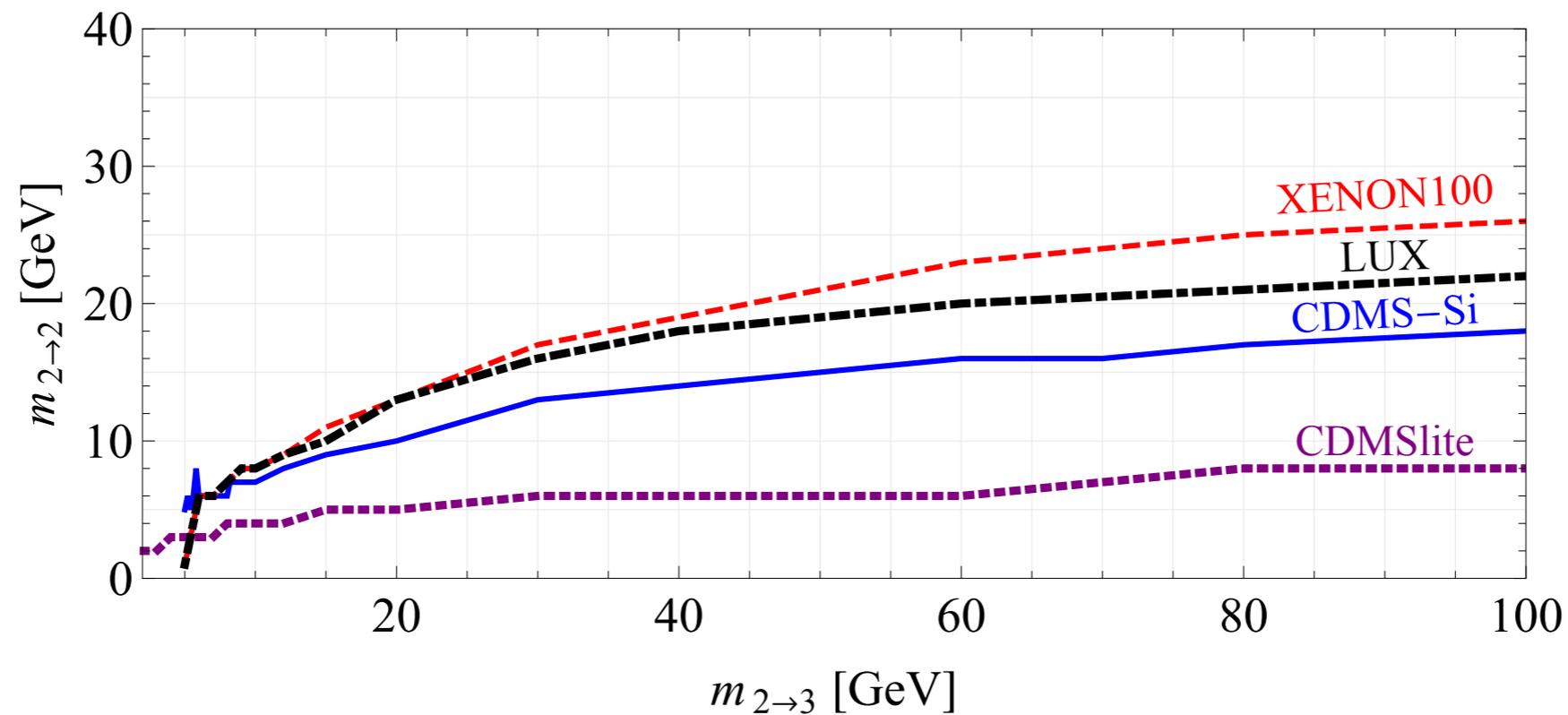


Mappings between 2to2 & 2to3



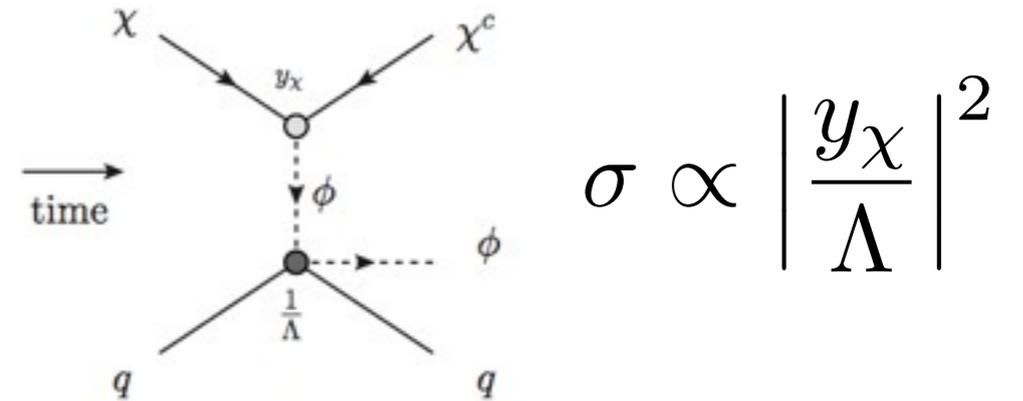
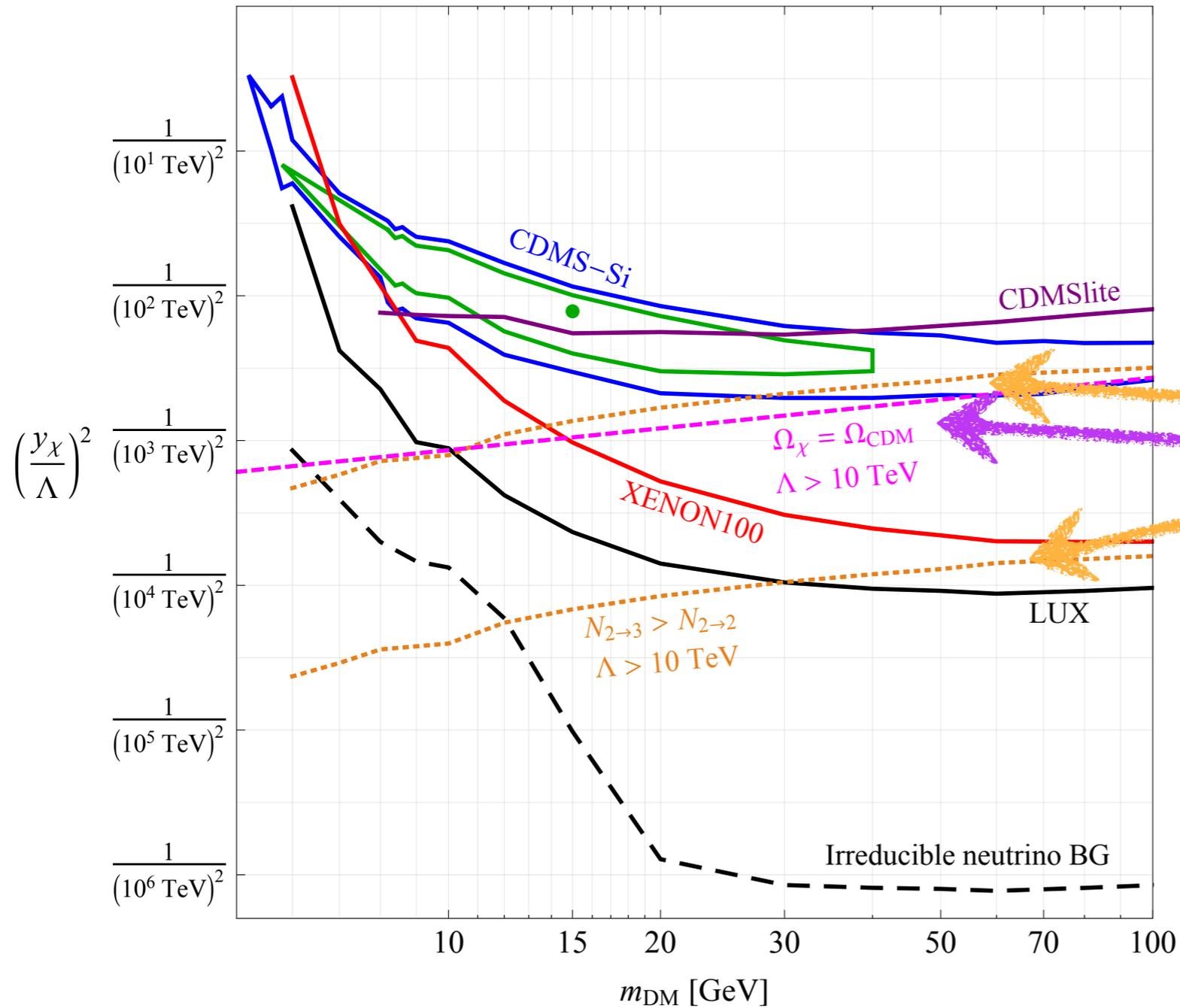
- hard to distinguish the shape difference
- heavy dmDM looks like a light WIMP DM
- since the m_χ of dmDM only shows up in $\mu_\chi N$ of the spectrum, the spectrum is insensitive to the DM mass when it is heavy

Pseudo-light Dark Matter

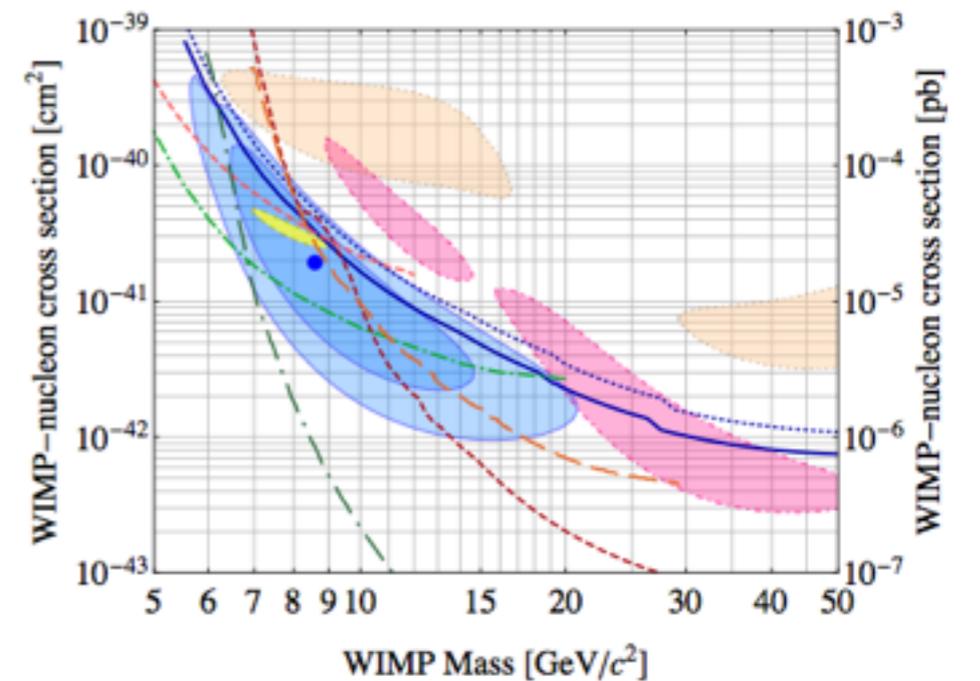


- 100 GeV DM fakes a 10 GeV WIMP
- different masses at different experiments

Interaction vs. mass

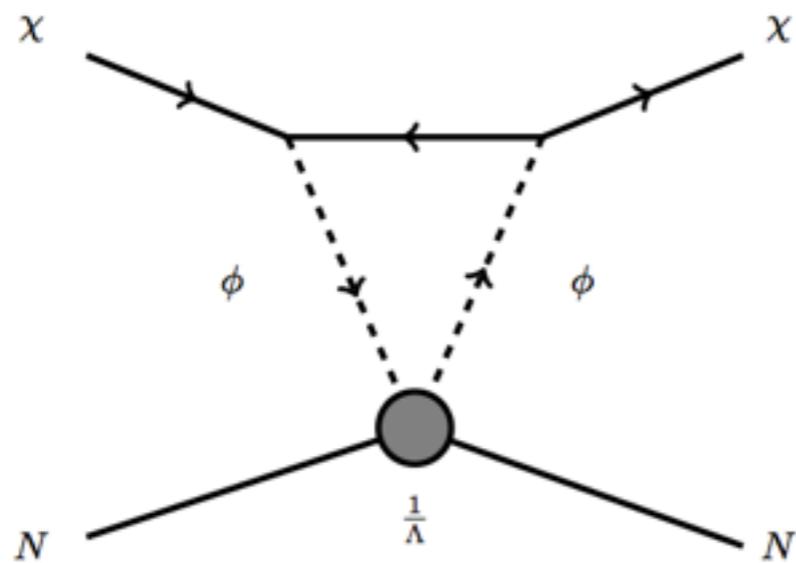


upper bounds for a given DM- ϕ coupling



Loop-induced 2 to 2 process

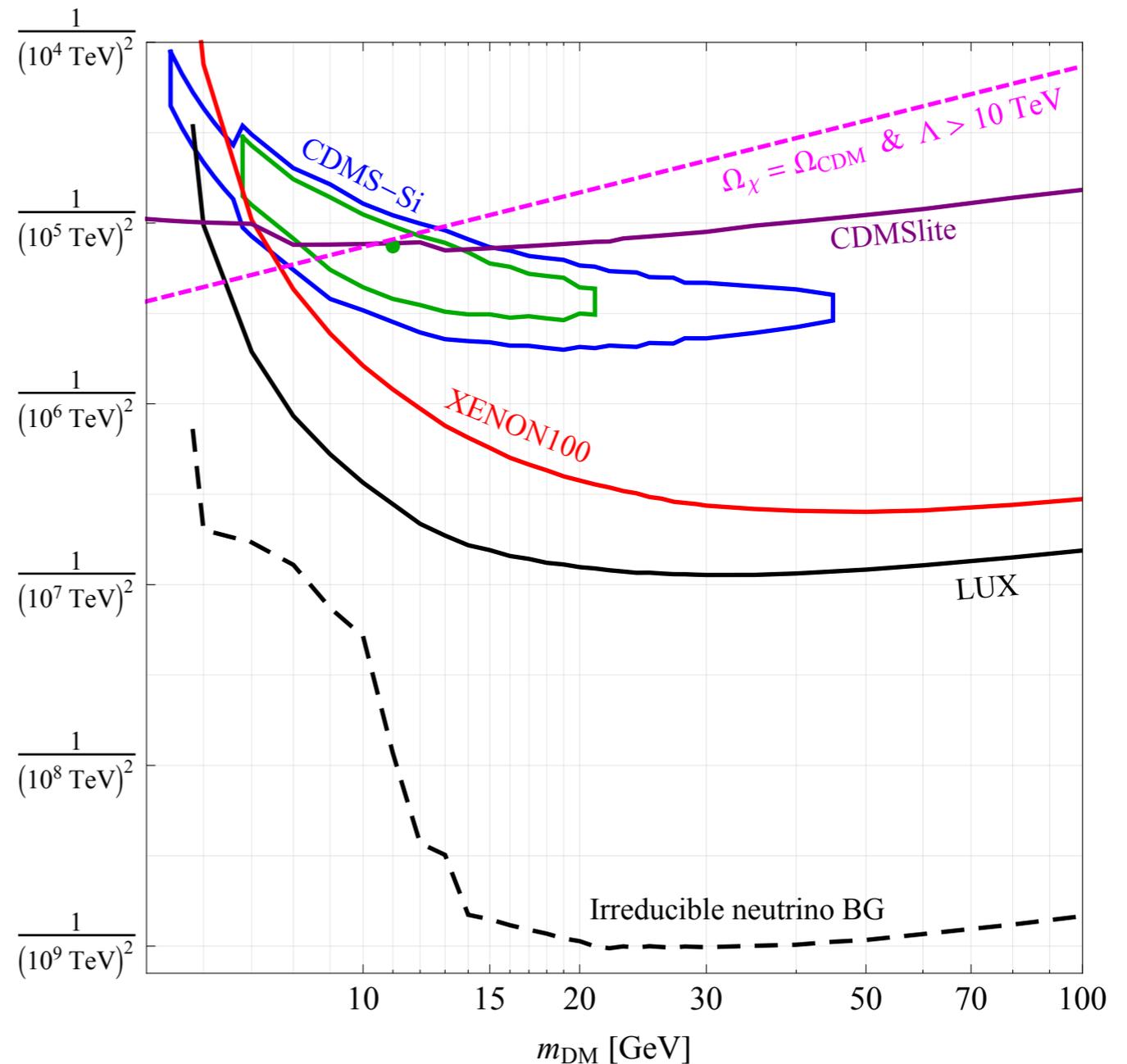
The simplest model also generates a 2 to 2 scattering



$$\approx \frac{y_\chi^2}{2\pi^2} \frac{1}{\Lambda q} (\bar{\chi} \chi \bar{N} N)$$

$$q = \sqrt{2m_N E_R}$$

$$\left(\frac{y_\chi^2}{\Lambda}\right)^2$$



Can be avoided in the $n_\phi = 2$ model, otherwise $y_\chi < 10^{-3}$

Possible applications of dmDM

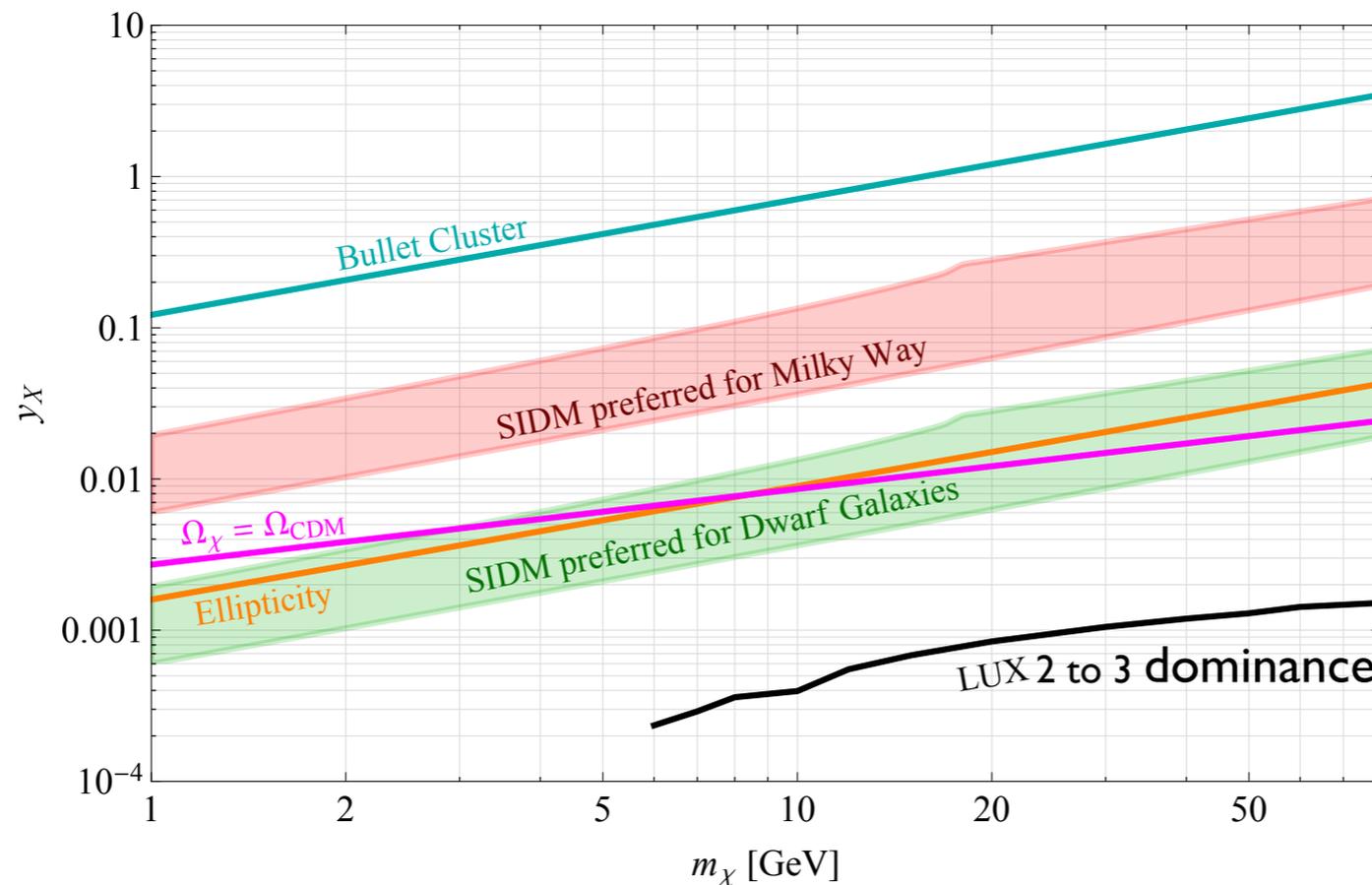
SIDM

E. Carlson, M. Machacek and L. Hall (92) , D. Spergel and P. Steinhardt (99)

The light mediator required for the 2 to 3 scattering makes the DM mediation to be an SIDM

$$\sigma_T/m_\chi \simeq \frac{y_\chi^4}{\pi m_\chi^3 v^4} \ln \left(\frac{4\pi m_\chi v^2}{2 y_\chi^2 m_\phi} \right) \simeq 0.5 - 30 \text{ cm}^2/\text{g}$$

S. Tulin, H-B Yu and K. Zurek (13)

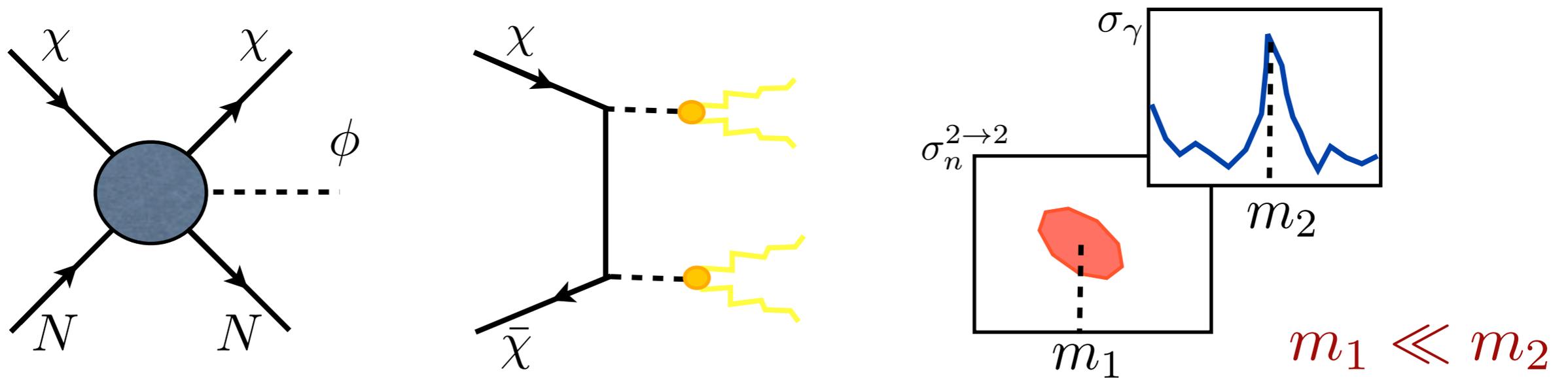


$$v = 300 \text{ km/s}$$

$$v = 30 \text{ km/s}$$

Decouple the (in-)direct mass

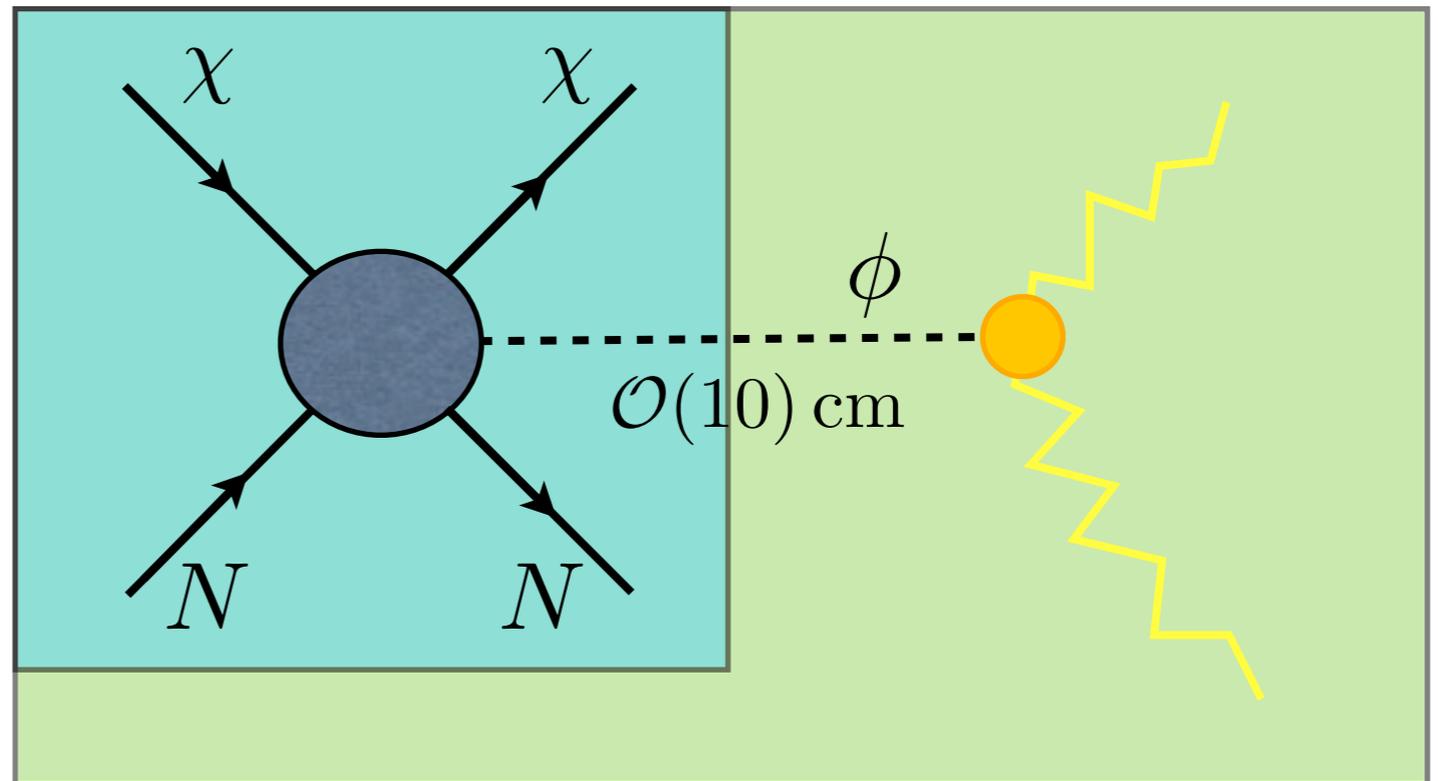
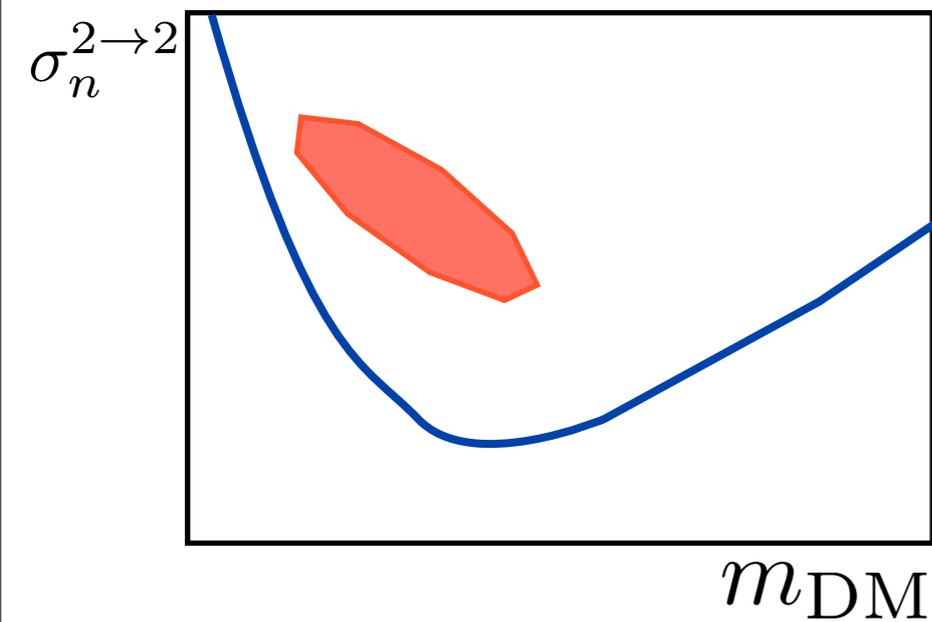
Direct detection underestimates the mass,
but in-direct detection does not



May explain the larger mass seen at in-direct detections

Avoid bound from large detectors?

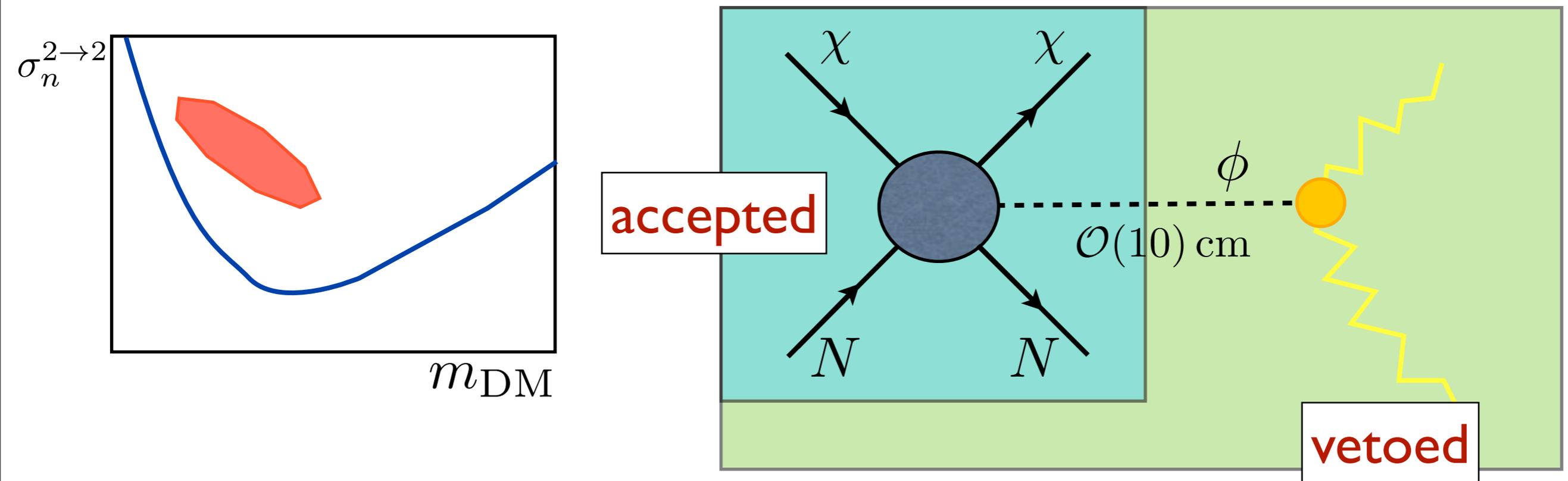
eg. reconciling signals (small detector) and exclusion bounds (large)



- if this is the case, having a larger detector will not help!
- the $\phi F_{\mu\nu} \tilde{F}^{\mu\nu} / \Lambda$ coupling needs to be large, with $\Lambda < \text{GeV}$ unless the DM velocity is large (~ 0.01) so $m_\phi \sim \text{MeV}$ and Λ can be of 100 GeV scale

Avoid bound from large detectors?

eg. reconciling signals (small detector) and exclusion bounds (large)



- if this is the case, having a larger detector will not help!
- the $\phi F_{\mu\nu} \tilde{F}^{\mu\nu} / \Lambda$ coupling needs to be large, with $\Lambda < \text{GeV}$ unless the DM velocity is large (~ 0.01) so $m_\phi \sim \text{MeV}$ and Λ can be of 100 GeV scale

Conclusion

dmDM is the first DM model featuring $2 \rightarrow 3$ direct detection, and hence adds new kinematics to model builder's tool box

Heavy DM candidates **fake light WIMPs** at direct detection experiments

Many possible applications: SIDM and different possibilities of reconciling different DM observations